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FLUID AMPLIFIER
APPLICATION STUDIES

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FLUID AMPLIFIER APPLICATION STUDIES

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GENERAL ELECTRIC COMPANY
Schenectady, New York

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ABSTRACT

This report summarizes the work performed under Phase II of "Research and Development - Fluid Amplifiers and Logic" for the National Aeronautics and Space Administration George C. Marshall Space Flight Center under contract No. NAS 8-5408.

The Phase II work consisted of studies to determine which applications of fluid amplifiers would be advantageous to NASA. It has been concluded that the best applications for further study are: 1) replacement of electronic amplifiers and networks of gas servos for engine actuation, and 2) a digital integrator which forms the fundamental building block for nearly all digital computation and control. Advantages of using fluid amplifiers for these applications are primarily environmental tolerance and the potential of higher reliability. A brief comparison of fluid amplifier and electronic reliability is included in this report. Since so many applications depend on the reliability advantages of fluid amplifiers, reliability has been defined as a "missing link" in the technology. Another "missing link" badly needed in this field is standardization of terminology, definitions, and data presentation.

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Section 1

INTRODUCTION AND SUMMARY

1.1 TOTAL PROGRAM PLAN

This report summarizes the work carried out under Phase II of a program conducted for the George C. Marshall Space Flight Center by the General Electric Company to determine the most promising National Aeronautics and Space Administration applications of fluid amplifiers.* The program is being carried out in three phases:

Phase I   - State-of-the-art Survey
Phase II   - Application Studies
Phase III - Missing Link and Demonstrator Development

Phase I, State-of-the-art Survey, was made by: 1) contacting all the laboratories known to be carrying out significant fluid amplifier work; and 2) a comprehensive literature search. The information gathered from the searches and laboratory contacts was compiled into a Phase I summary report. The report also includes conclusions regarding development status of fluid amplifiers and suggests areas requiring emphasis for accelerating their development. (NASA CR-101, October 1964)

With these results as background information, Phase II, Application Studies, was carried out to determine the NASA applications in the space mission where fluid amplifiers could be used to improve performance or reliability, or to make possible systems which cannot be implemented with existing control components. This report summarizes the results of these studies.

During Phase III demonstrators and missing link development work will be carried out based on the results of Phase II. The specific areas or applications to be developed will be selected jointly by the National Aeronautics and Space Administration and the General Electric Company.

1.2 APPROACH - PHASE II APPLICATION STUDIES

The overall objective of Phase II was to determine the most promising NASA applications of fluid amplifiers and to identify "missing links" or weak areas in this new technology. The approach used in reviewing possible fluid

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* For this contract, fluid amplifiers are defined as that class of fluid interaction devices, sometimes called "pure fluid amplifiers", which are characterized as having no moving parts.

amplifier applications was to make use of experts or "consultants" throughout the General Electric Company; each being an authority on a certain aspect or segment of NASA interests. Over twenty Company engineers and scientists were assigned to contribute to the program, to determine applications and to supply data to the fluid amplifier application engineers. The consultants with their specific areas of interest are listed in Appendix I.

Figure 1-1 is a block diagram representation of the study approach and working relationships between the application engineers and the consultants. At the initial contact, the consultants' fluid amplifier knowledge was updated with a presentation to reflect the present state-of-the-art. The Phase I survey provided a comprehensive source of information for this presentation. General descriptions and characteristics of the known fluid elements, sensors, transducers, and circuits were described to stimulate the consultants' application thoughts. Individual conferences with each consultant were then held to provide more detail in areas of particular interest.

The second step (Figure 1-1) in the application studies was a submission of preliminary application ideas by each of the consultants to the application engineers. At this point, the suggested applications generally were in the form of block diagrams with each block identified as having gross or general characteristics. After the first review, the application block diagrams were revised and laid out in more detail. Circuit detailing and implementing of the functional characteristics of the larger blocks were carried out. In many cases, this work proceeded to suggested fluid amplifier circuit schematics. This work was carried out primarily by the consultants.

At the second review, the consultants' application work was taken over by the fluid amplifier application engineers for further refinement. The work from this point on entailed analytical studies where possible to investigate the application on a quantitative basis as compared to the qualitative nature of the study up to this point. The analytical work included trade-off considerations in several instances where numerical data were available on the application requirements. The data gathered in the Phase I survey proved to be most helpful at this point. The results from the second review and the analytical studies were then prepared
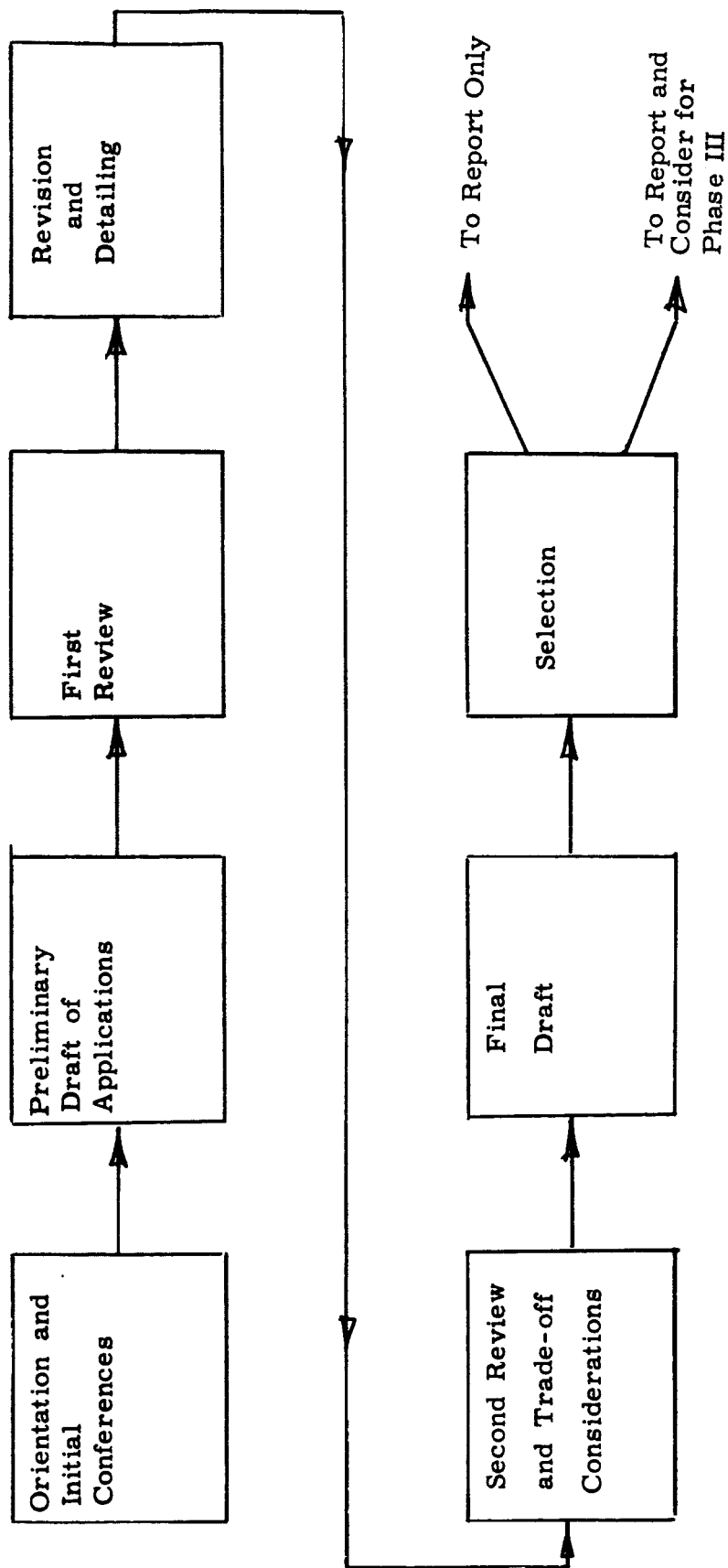
Figure 1-1.   Block Diagram of Application Studies.

in final draft form for inclusion in this report and for review with the National Aeronautics and Space Administration for selection of the Phase III activities.

In order to limit the vast number of possible applications to those in which fluid amplifiers represent a true advantage, several criteria were used by the consultants when an application was considered. The criteria were:

1. The fluid amplifier must perform a function or perform in an environment which is impossible or impractical with more conventional control techniques.

2. The use of fluid amplifiers must show promise of a significant improvement in performance over conventional control techniques.

3. Assuming the inherent high reliability of fluid amplifiers is proven, the reliability of the fluid amplifier system must show a significant improvement over the existing or more conventional system.

4. The fluid amplifier system must be practical, i.e. the system or element requirements must not exceed the foreseeable capabilities of fluid amplifiers.

A suggested application, in order to receive consideration, had to meet criterion 1, 2, or 3 and criterion 4. The use of these criteria reduced the large number of suggested fluid amplifier applications where they would be used only because they provide another means of performing the desired function. The mass of information was reduced to a manageable number of suggested applications in which there is a specific advantage in their use. The above criteria were continuously applied throughout the application studies to cull out applications that could not be justified. Concurrently, applications that were functionally similar were combined into a single study to avoid duplication. This approach narrowed the promising areas of application to a few highly advantageous and specific applications which have made the selection of Phase III work orderly and rational.

1.3 SUMMARY OF STUDY RESULTS

It became apparent during the course of this study that three categories of fluid amplifier applications were resulting from this work. The first category has been identified as "Feasible Applications"; those applications which meet

the criteria summarized in the previous section. The second category, "Possible Future Applications", is a listing of applications that either do not meet the criteria or are not within the scope of the program. In some instances, these applications were cases where fluid amplifier implementation could be envisioned, but the reasons for their use could not be justified at present. The third category was a listing of "Problem Statements", suggested areas of application where a problem presently exists but a solution to the problem, even with the use of fluid amplifiers, is not known. The problem statements thus are applications in which control, logic, or sensing concepts must be innovated or developed before the advantages of using fluid amplifiers can be determined.

The listings below represent a final summary of the applications suggested by the consultants. In many cases applications suggested by several consultants were so similar that they were combined into one typical application.

1.3.1 FEASIBLE APPLICATIONS

1. Position Servo for Engine Actuation

   Description: Gas servos for gimballing engines are being developed in preference to hydraulic actuation since they are compatible with liquid hydrogen temperatures experienced during shut down. The electronic amplification and compensation in the servoloop can be replaced with fluid amplifiers.

   Advantages: Fluid amplifiers could perform this function with higher servo system reliability; the servo would be a selfcontained package using a compatible power fluid.

   Discussed in: Section 2

2. Reactor Rod Servo

   Description: Gas servos are under development for positioning control rods for reactors such as used in the NERVA engine. Electronic amplification and compensating networks could be implemented with fluid amplifiers which can be placed near the reactor in the radiation and temperature environment.

1-5

Advantages: Temperature and radiation tolerance; the servo can be an integrated package with no shielding required.

Discussed in: Section 2

3. **Position Servo for Experiments**

Description: Erection and alignment of experiments or solar cell paddles on a satellite may be performed with gas servos. Amplification and frequency shaping networks are needed in the loops to obtain the desired performance. The position servos may use analog or digital implementation. Fluid amplifiers could meet the performance requirements.

Advantages: Radiation tolerance; insensitivity to sterilization temperatures; reliability.

Discussion in: Sections 2 and 4 discuss similar devices.

4. **Lifeboat Guidance and Control System**

Description: Space stations eventually will incorporate an emergency escape and re-entry vehicle, a space lifeboat. Guidance and control aboard the lifeboat will be minimal but must be highly reliable after long periods of nonuse. The system must operate after accidental exposure to radiation. Requirements appear consistent with fluid amplifier capability.

Advantages: Long shelf life; reliability; radiation tolerance.

Discussed in: Sections 3 and 4

5. **Attitude, Navigation, and Guidance Computers for Satellites or Other Space Vehicles**

Description: These functions generally are performed with digital computation. In many cases (for space applications), the complexity of the system and the required iteration rates may be compatible with fluid logic. In the future, packing density of fluid amplifiers may be increased so that system size is not a limitation.

Advantages: Reliability; in some instances radiation tolerance.

Discussed in: Sections 3 and 4 discuss digital computation.

6. Speed Regulator for Space Turbine Power Plant

Description: One type of space power plant under development is a reactor heated Rankine cycle. Reactor heat energy will boil liquid metal to produce vapor for the cycle. The flow rate of vapor must be controlled to regulate turbine speed. The flow of liquid metal can be controlled with fluid amplifiers to obtain this regulation using a pump bypass arrangement.

Advantages: High temperature and radiation tolerance; long life.

Discussed in: Section 5

7. Temperature Regulator for Liquid Metal Coolant Loop

Description: Space systems under consideration will utilize liquid metal coolant loops to reject heat to space. Temperature in the radiator must be kept above a minimum value to prevent liquid metal freezing. A fluid amplifier is used in the temperature control.

Advantages: High temperature capability; long life; and radiation tolerance for applications on a nuclear power plant.

Discussed in: Section 5

8. Tactual Perception

Description: A means of conveying information to an astronaut when normal means, such as sight and sound, are impractical due to high g forces is the use of force patterns on the skin. The use of air jets for producing the force patterns is presently under investigation. Fluid amplifiers could be used in tactual perception control loops for logic and information storage.

1-7

Advantages: Reliability; transducers are minimized if logic is performed
                    pneumatically.

Discussed in: Section 6

9.   Cabin Leak Detector
    Description: A highly reliable indicator of cabin leakage is needed
                    which is independent of the vehicle's electrical system or
                    other systems. Cabin leakage can be detected by fluid
                    amplifier devices.

    Advantages: Reliability; simple; self contained; and minimum of trans-
                    ducers.

    Discussed in: Section 7

10. Secondary Injection and Fuel Oxidant Control
    Description: The use of main engine gas for secondary injection appears
                    feasible with the use of fluid amplifiers for valving. With
                    the development of sensors, fluid amplifiers also appear
                    practical for controlling fluid/oxidant ratio.

    Advantages: Environmental tolerance (temperature and vibration).

    Discussed in: Section 8

1.3.2 POSSIBLE FUTURE APPLICATIONS

Several applications were suggested which could use fluid amplifier cir-
cuits but did not meet the criteria of paragraph 1.2. These applications, listed
below, are identified as "possible future applications" because application
advantages may appear at a later date as the development of fluid amplifiers
proceeds or if emphasis on application areas should shift.

Application	Reason for Future Considerations
Biological research	Outside program scope
Aircraft flight controls	Outside program scope
Alignment of water launch booster	Booster development not firm, no obvious advantage now

Application	Reason for Future Considerations
Timer programmer	Functional assembly - not an application
Gas bearing servo	Functional assembly - not an application

1.3.3 PROBLEM STATEMENTS

The problem statements listed below need solutions. At this time, the use of fluid amplifiers suggests no approaches which appear practical; further consideration and innovation are required to develop good solutions. When a potential solution is available for any of the statements, it should be reviewed to consider fluid amplifier implementation.

Control slosh of liquid fuels and oxidants

Cryogenic fuel handling

Fuel line leak detection

Fuel cell cooling control

Mass flow monitoring

Re-entry velocity measurement

Measurement of cryogenic fuel boiloff rate

Measurement of astronaut suit pressure

Measurement of turbulence in fuel flow

Switching of pressure sources

Fault location and correction in coolers

Sensing of re-entry temperature profiles

Flotation control for water recovery

Center of gravity controller (liquid pumping)

1.4 SELECTED APPLICATIONS AND MISSING LINKS

From the review of the possible NASA applications, two appear to be the most appropriate for the application of fluid amplifiers. These applications and reasons for their choice follow:

1. Gas Servos for Engine Actuation -- A relatively simple application requiring no significant advancement in the state-of-the-art nor missing link developments, such as sensors or transducers. This

application would eliminate electronic amplifiers and provide a self-contained actuator package. The application is timely since gas servo engine actuators are presently under development. The development time for fluid amplifier circuitry is relatively short, compatible with the gas servo development cycle.

2. <u>Digital Integrator</u> -- Several applications (e.g., space lifeboat deorbit computer, navigational computer, attitude control, and logic) that appear attractive because of long shelf life and potential reliability of fluid amplifiers use digital computation. All these applications use a common building block -- the digital integrator -- in their implementation. The development of this building block is the typical first step in developing digital computation systems. For practically all applications, the digital integrator should have the same general characteristics, viz., small size, highest possible speed (at least one kc clock rate), and low power consumption. Development of this one component, therefore, can be aimed at goals to satisfy most digital computation applications. The digital integrator is a sufficiently complex circuit to represent a task with a somewhat longer development time scale than the engine actuator described above.

The review of possible applications has also revealed "missing link" areas, i.e., areas where particular fluid amplifier devices do not exist or the technology itself is lacking. Numerous missing links, specific to a particular application, were identified during the course of this study. Even more significant, however, was the determination of two areas where the technology is lacking. These two areas, which are universal needs for all applications, are:

1. <u>Reliability</u> -- Data on fluid amplifier reliability apparently is non-existent. This is not surprising because of the relatively early state-of-the-art. It is important, however, to initiate reliability work at this early time because one of the principal advantages of fluid amplifiers appears to be their long life (operating and shelf life).

Even though the devices are still in the development stage and experience with circuits is limited, it is possible to begin reliability work by defining failure modes, investigating the physics of failure, and designing experiments to measure reliability.

2.   Standardization -- Like most new fields, there is a lack of standardization in the fluid amplifier field which could be relatively easily corrected if work is initiated at this time.   There is a lack of standardization in nomenclature, definitions (such as gain, output power, and noise figures), and even in terminology.   Standardization of a few key terms and definitions would greatly enhance the interchange of technical information in this field.

1.5   REPORT CONTENTS

The following sections of this report discuss the selected applications in more detail.   The engine actuator and digital integrator (Sections 2 and 3) are treated rather extensively because they were selected as key areas which will be followed further in Phase III of the program.   Section 5 describes the use of fluid amplifiers in liquid metal loops such as are contemplated for the SNAP systems.   While there is now some question as to the future of SNAP, the applications considered are typical of those which meet the selection criteria of severe environments for which suitable conventional components cannot presently be found.   The Tactual Perception System (Section 6) is an example of a system still in very early development but which appears to be a natural "fit" for fluid amplifiers.

Section 9 considers the question of fluid amplifier reliability and is a related study rather than an application.   Possible failure modes are assumed and a numerical reliability comparison is made between fluid amplifier and electronic circuits which are functionally equal.   A study was also made of the use of bottled gas for power supplies (Section 10).   Graphs are presented from which supply volume and pressure can be estimated for fluid amplifier circuits.

Appendix I lists the consultants who contributed to the application studies

and their areas of specialty. Appendix II defines the schematic representations for fluid amplifiers which have been used in this report.

Section 2

GAS SERVOS FOR ENGINE ACTUATION

2.1 SUMMARY

Gas servos presently are under development for engine actuation and for reactor rod control. These systems use conventional electronic components for feedback, amplification, and compensation networks. These applications were investigated to learn if fluid amplifiers could be used to perform these functions or to replace the servovalve. It has been concluded that fluid amplifiers could be applied advantageously to these position servos, and that the present state-of-the-art of fluid amplifiers is such that no major break-throughs, or missing-link developments, are required for the development of an experimental system. The major advantages would be realized in the control circuits, gas consumption is excessive for replacement of the servovalve.

The use of fluid amplifiers for these applications should provide a significant improvement in reliability of the servo system. The resulting system would be a self-contained package housing the power valve, actuator, feedback transducer amplifiers, and compensation networks. This unitized package concept is possible, with its potential in improved reliability, because of the good environmental tolerance of fluid amplifiers. The engine actuator application will require operation on -250F hydrogen under high vibration. Nuclear rod actuators must tolerate the high radiation adjacent to a reactor. The fluid amplifier design for both of these environments is straightforward based on today's state-of-the-art and appears to pose no problem other than a judicious choice of fabrication materials.

The discussion that follows pertains to the engine actuator. The study for applying fluid amplifiers to reactor rod control previously had been carried out under contract with the National Aeronautics and Space Administration, Lewis Research Center (Ref. 2-1). Although the two applications are quite different in the power levels required of the servo, they require very similar feedback,

Ref. 2-1 Boothe, W.A., "Feasibility Study - Application of Fluid Amplifiers to Reactor Rod Control," Report No. CR-54005, NASA Lewis Research Center. Work performed by the General Electric Company under contract No. NAS 3-2567.

compensation networks and signal amplifiers. Both operate on low temperature hydrogen. The circuitry arrived at and the conclusions reached generally apply to both systems.

The system considered in the study is a gas servo to actuate the gimbal-mounted J-2 engine. The requirements of the servo loop system were developed under a previous study (Ref. 2-2). A block diagram of the loop is shown in Figure 2-1. The shaded blocks represent functions that may be implemented with fluid amplifiers (in the conventional gas servo these functions are implemented with electronic devices).

Results of the application study showed that fluid amplifiers could be used for the functions shown in Figure 2-1 based on today's state-of-the-art. A concept for the position feedback transducer was developed during the study because no such devices were known. The concept appears practical and should not require any advancement in the state-of-the-art for development. Gas consumption for the fluid amplifier circuitry is predicted to be 0.407×10^{-3} pounds per second (-250F Hydrogen)as compared to 1.5×10^{-3} pounds per second quiescent flow for the servovalve. Replacement of the closed-center servovalve with a beam deflector proportional amplifier was considered but is impractical because of the high gas consumption. Since the beam deflector is a constant flow device, it would have a continual consumption equal to the peak flow requirements of the actuator. This high consumption is well beyond the maximum permissible; therefore, replacement of the servovalve with a proportional amplifier was considered no further. The use of vortex amplifiers or valves which have characteristics approaching closed-center characteristics was considered. This approach was also dropped because data available on the vortex valves are not sufficiently complete for a detail study. Also, with present vortex valves the input-signal pressure levels generally are somewhat higher than the inlet pressure level. The supply pressure to this power valve would have to be dropped or a separate high pressure supply would be required for the signal portion of the loop (summation, compensation, and driver amplifiers). Both possibilities were concluded to be

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Ref. 2-2. "Pneumatic Actuation System," proposal submitted to Astrionics Laboratory NASA in response to RFQ TP 3-33014, October 5, 1962.
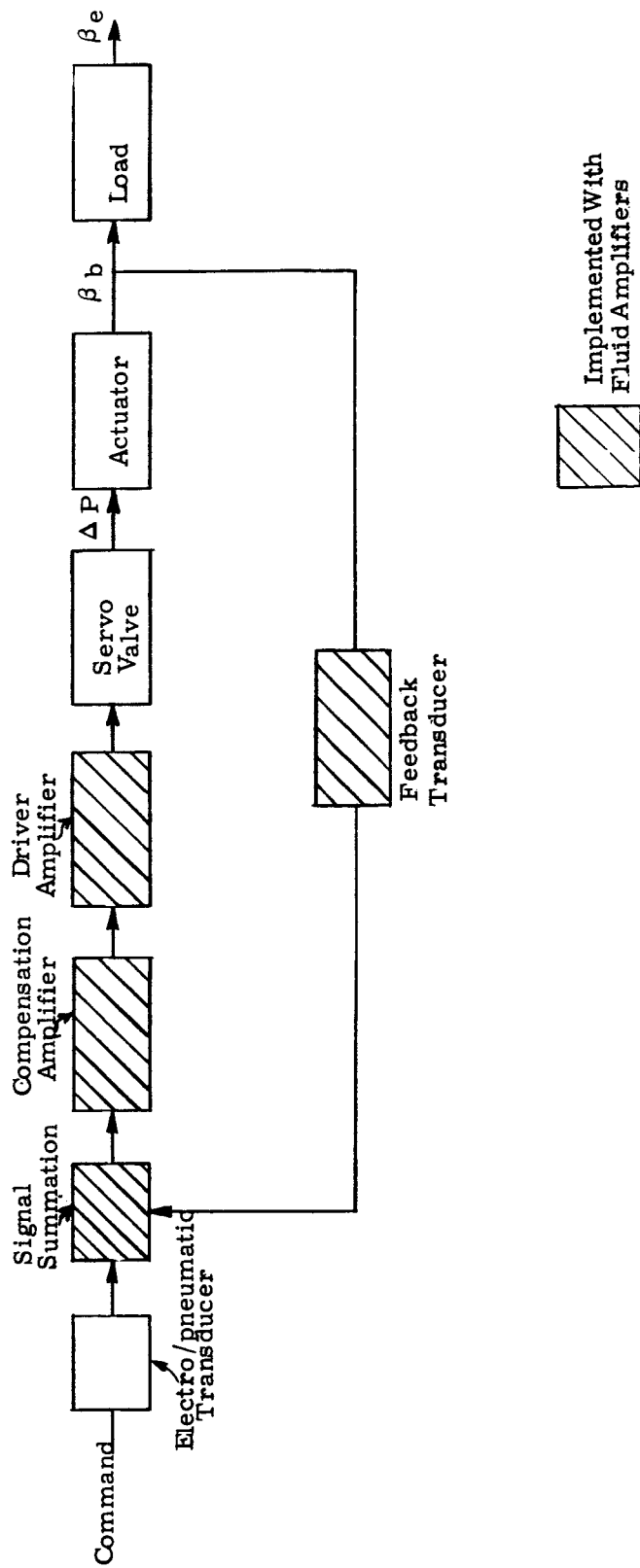
Figure 2-1. Block Diagram of Engine Actuator.

impractical, so vortex valves were no longer considered for use as the servo valve.

2.2   SYSTEM DESCRIPTION AND PERFORMANCE

A block diagram of the servo loop is shown in Figure 2-2. Values for the time constants T_1 and T_2 and the loop gain were taken from a previous study (Ref. 2-2). Response requirement was a maximum of 20° phase shift at one cycle per second. Stiffness required was 500,000 pounds per inch at one cycle per second. For purposes of this fluid amplifier application study, the block diagram in Figure 2-2 was simplified and rearranged so as to appear as in Figure 2-3. The major simplification is omission of the position error limit. Test results on another gas servo application showed that the error limit was not required. (Further systems analysis beyond the scope of the present studies will be necessary to verify this for the J-2 application). This limit function could be implemented at a later date with fluid amplifiers if necessary. Load friction was also neglected in the loop shown in Figure 2-3. This simplification will not change the studies of the fluid amplifier imple- mentation at the forward end of the loop. The block diagram shown in Figure 2-3 has been rearranged to demonstrate more easily the requirements of the fluid amplifier circuitry. From this diagram, it can be seen that the fluid amplifier circuitry must:

1.   Sense the actuator position (β_p)
2.   Provide a summation of β_p and the command signal
3.   Provide the lead-lag characteristics with time constants defined by T_1 and T_2
4.   Provide the necessary loop gain by means of fluid amplifiers (K_A). The error signal will require amplification to a level sufficient to drive the servovalve. This driver amplifier will provide the interface between the fluid amplifier portion of the loop and the servovalve.

Each of these four areas is discussed in detail in the following paragraphs.

Figure 2-2. Block Diagram of J-2 Engine Actuator.
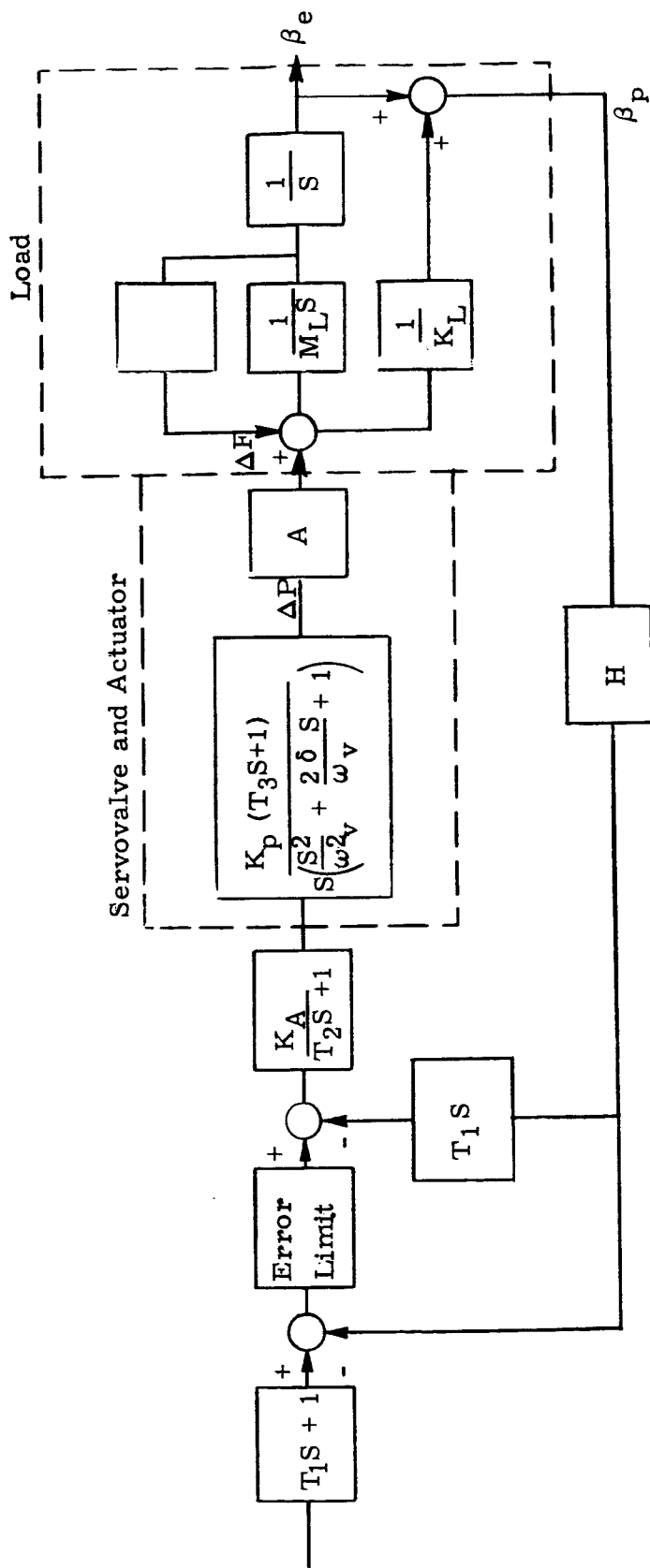
T_1 = 0.005
T_2 = 0.005
T_3 = 0.5
δ = 0.2

$HK_A K_P T_3 A$ = 500,000 lbs/in

A = Actuator area
M_L = 116.7 lb-sec^2/in
K_L = 223,000 lbs/in
Load damping 0.025
ω_v = servo valve natural frequency
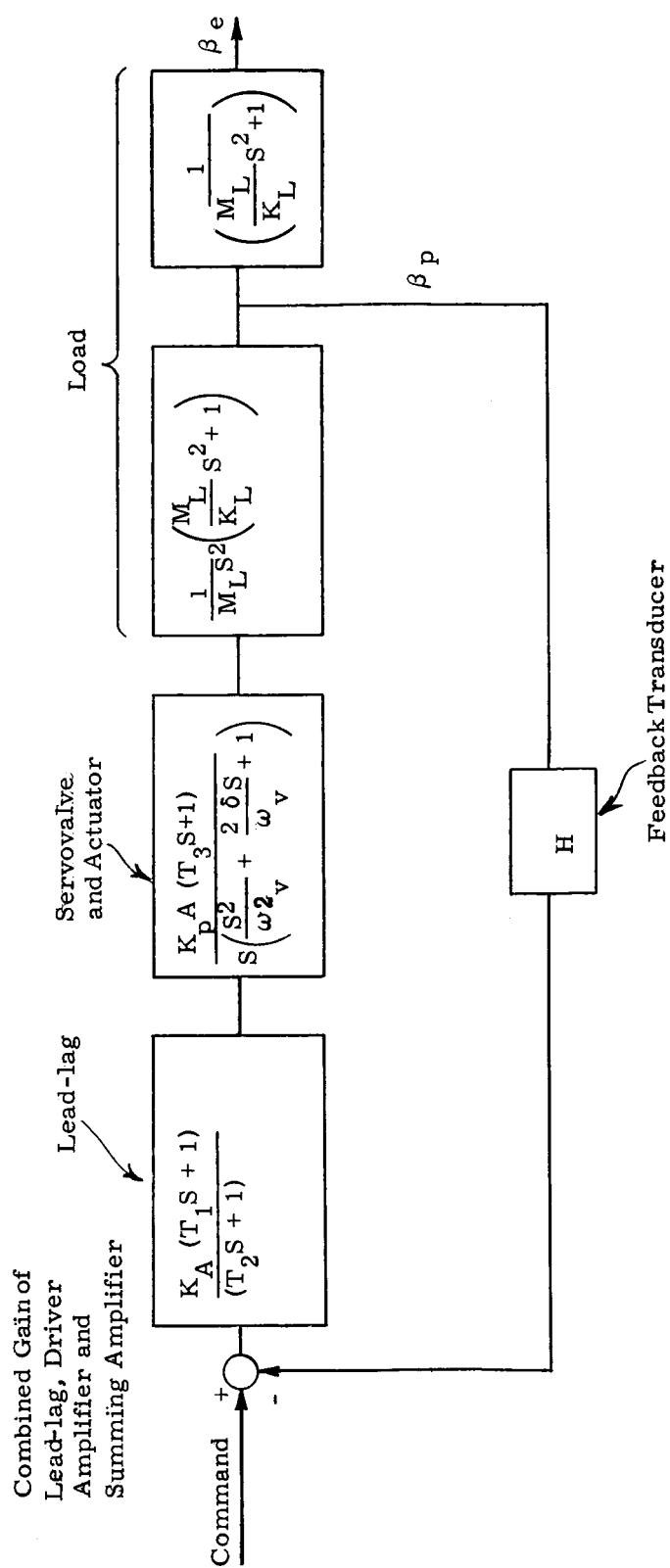
Figure 2-3. Reduced Block Diagram.

2.3 LEAD-LAG CIRCUIT

As shown in Figures 2-2 and 2-3, the lead-lag circuit will have a transfer function of

$$\frac{\Delta Po}{\Delta Pi} = \frac{-K_L (T_1 S + 1}{(T_2 S + 1)} \tag{2-1}$$

The time constants have numerical values as follows:

$$T_1 = 0.05 \text{ second}$$
$$T_2 = 0.005 \text{ second}$$

The gain of the lead-lag circuit, K_L, is not important at this time since the total loop gain will be adjusted after the gain of each block is established. The fluid amplifier circuit selected to provide the lead-lag characteristics is shown in Figure 2-4. Figure 2-5 is a block diagram of the lead-lag circuit. An analysis was carried out under a previous program (Ref. 2-2) and only the results will be listed here. The steady-state gain becomes:

$$K_L = + \frac{1}{G_2 + \dfrac{1}{G_1}} \tag{2-2}$$

Where G is the pressure gain of the amplifiers. The time constants are defined as

$$T_1 = \frac{K_{F2} C}{1 + \dfrac{K_{F2}}{K_{C1}}} \tag{2-3}$$

and

$$T_2 = \frac{T_1}{G_1 G_2 + 1} \tag{2-4}$$

Here

$$C = \frac{V_c}{\gamma RT} \tag{2-5}$$

Where V_c is the volume C in the feedback line. K_{F2} and K_{C1} are constants for the amplifiers (Ref. 2-2) which numerically are

$$K_{F2} = 0.55 \frac{P_{S2}}{W_{S2}}$$
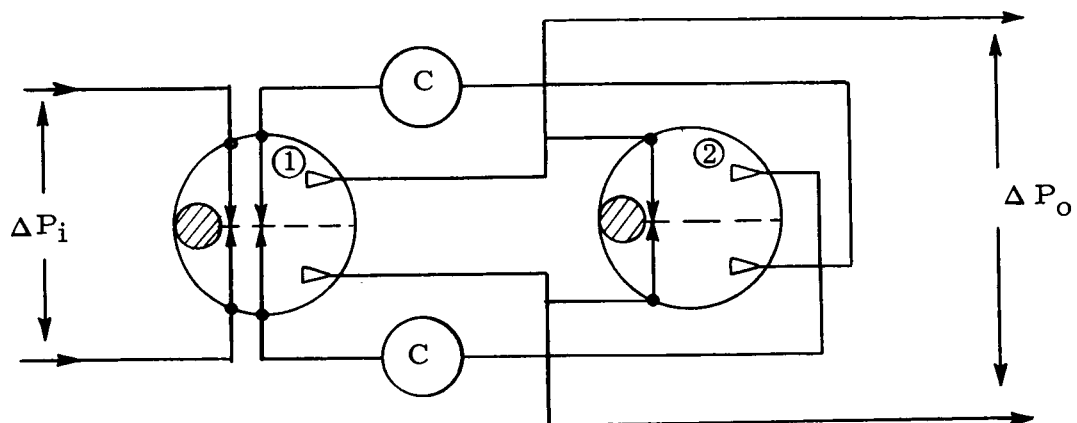
Figure 2-4. Schematic Diagram of Lead-Lag.
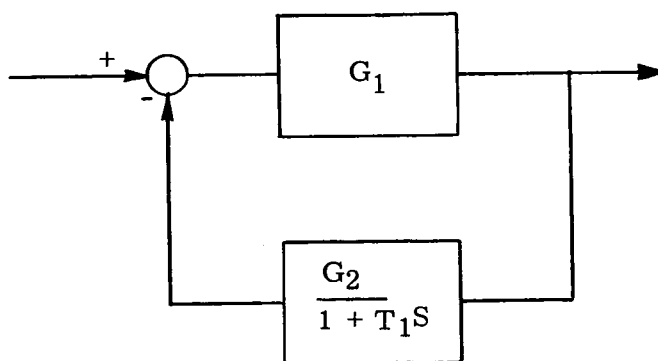
Figure 2-5. Block Diagram of Lead-Lag Circuit.

$$K_{C1} = 0.50 \frac{P_{S1}}{W_{S1}}$$

Further evaluation of the numerical constants required selection of the amplifier size and operating pressures. The nozzle size selected was 0.010 inch by 0.010 inch. The supply pressure used was 46 psia with an exhaust or back pressure of 36 psia. With hydrogen at -250F as the working fluid, the power nozzle weight flow is

$$W_S = 0.378 \times 10^{-4} \text{ pounds per second}$$

The amplifier constants are then calculated to be

$$K_{F2} = 0.55 \frac{P_{S2}}{W_{S2}} = 1.46 \times 10^5 \frac{\text{pounds per square inch}}{\text{pounds per second}}$$

and

$$K_{C1} = 0.50 \frac{P_{S1}}{W_{S1}} = 1.32 \times 10^5 \frac{\text{pounds per square inch}}{\text{pounds per second}}$$

The same supply pressure drop ($10 P_{S1}$) was used for both amplifiers so that $P_{S2} = P_{S1}$ and $W_{S2} = W_{S1}$, using these values for the amplifier constants. The volumes, V_c, required to provide the pneumatic capacitance, C, for a time constant $T_1 = 0.05$ second were calculated (Eq. 2-3 and Eq. 2-5) to be

$$V_c = 1.93 \text{ cubic inches}$$

The time constant T_2 is investigated using Eq. 2-4. The pressure gains used for the amplifiers were

$$G_1 = 3.0$$

$$G_2 = 4.5$$

G_1 is lower since this amplifier must drive a succeeding amplifier as well as G_2. Evaluation of T_2 from Eq. 2-4, using these gains, shows that

$$T_2 = 14.5 \, T_1$$

This spread between T_1 and T_2 is slightly greater than the specified value of $T_2 = 10 \, T_1$ but will not detract from system performance since the lag T_2

is at a greater frequency than required. The steady-state gain is calculated from Eq. (2-1) to be

$$K_L = 0.311$$

The resulting numerical transfer function for the lead-lag circuit is

$$\frac{\Delta Po}{\Delta Pi} = \frac{-0.311 \left(1 + \frac{S}{20}\right)}{\left(1 + \frac{S}{290}\right)}$$

The power consumption for the network is

$$W_{S1} + W_{S2} = 0.756 \times 10^{-4} \text{ pounds per second}$$

2.4   DRIVER AMPLIFIER

The driver amplifier is a proportional fluid element used to amplify the signal level at the compensation networks to a value sufficient to drive the servovalve. The concept used in this study for coupling the driver amplifier to the servovalve is illustrated in Figure 2-6. The output ports of the driver amplifier are connected to bellows which have the moving ends attached to a flapper as shown in the illustration. The flapper rotates about the pivot to open and close nozzles on the servovalve. The flapper thus provides a point for force summation; the forces exerted by the bellows and those caused by pressure feedback in the nozzles are summed, resulting in a net force to deflect the flapper. In this arrangement, the bellows would replace an electro-mechanical torque motor on the present servovalve. Another possible coupling concept considered is to drive the first stage of the servovalve directly with the driver amplifier. The flapper concept was chosen because it provides better servovalve performance. The output pressure of this pressure-type servo-valve is determined by the first-stage pressure; the second stage is a flow amplifier with a pressure gain of about unity. The flapper-nozzle arrangement (Figure 2-6) provides a greater swing in differential pressure than a fluid amplifier. Use of a fluid amplifier to establish the pressures in the first stage of the valve would therefore lower the servovalve maximum output pressure differential and would require a larger actuator to provide the same maximum actuator output force.
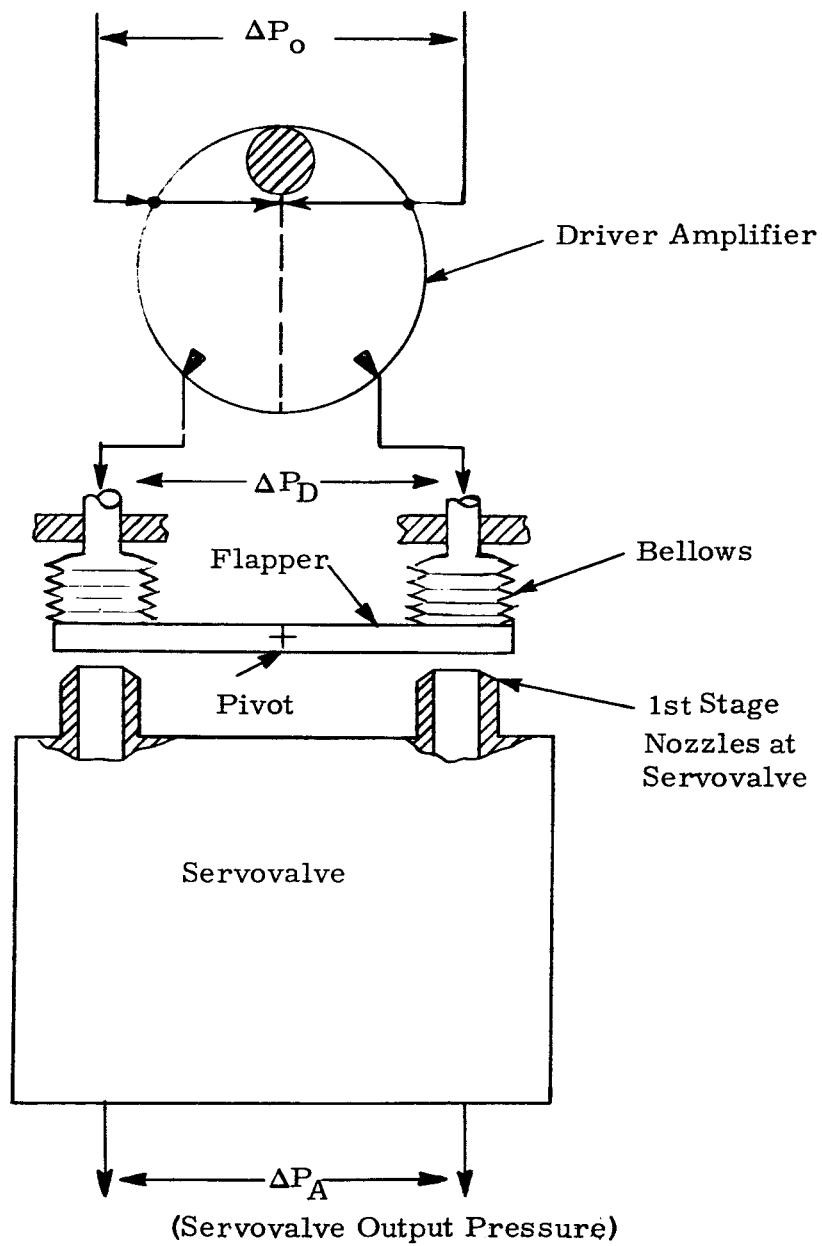
Figure 2-6. Schematic Diagram of Driver Amplifier.

A second reason for choosing the flapper arrangement is that a relatively low supply pressure can be used for the driver amplifier. A direct coupling of the driver amplifier with the servovalve would necessitate a supply pressure of 800 psig with a back pressure of 15 psia and lower. The resulting pressure ratios across the power nozzle would be supersonic and in a region where little performance data and few design techniques are known.

The sizing of the driver amplifier was carried out in the following manner: the force required to provide maximum deflection of the flapper was determined to be about three pounds (approximately two pounds pressure force and one pound bellows spring force). A bellows with an effective area of 0.11 square inch (0.375 in diameter) was selected as a compromise between a small size for easy mounting and a large area to minimize the required pressure. The maximum pressure output from a proportional amplifier is about 70% of the supply pressure drop. A supply pressure drop of 39 psi is therefore required to obtain three pounds of force (0.70 x 39 psi x 0.11 in^2). The back pressure on the driver amplifier was also chosen to be 39 psia in order to avoid supersonic pressure ratios and the associated shock losses. The supply total pressure then is 78 psi

The volume of the bellows on the output of the driver amplifier contributes a first order lag that could add significant phase lag in the frequency range of interest. The minimum frequency for this lag break, that would cause little phase shift in the region of loop crossover frequency, was established to be 1000 radians per second. The bellows volume corresponding to this lag was calculated to be 0.020 cubic inches or a maximum length of about 0.19 inch for the 0.375 inch diameter bellows. The nozzle size for the driver amplifier used in this calculation was 0.010 inch by 0.010 inch. The gas consumption for the amplifier with this size power nozzle and a pressure drop of 39 psig is 0.76 x 10^{-4} pounds per second. Since the bellows represent a blocked load, the pressure gain of the driver amplifier is higher than other loaded amplifiers. A gain value of eight was used for the driver amplifier in this study. The driver amplifier and bellows combination with the chosen parameter values has the following transfer function:

$$\frac{\Delta F_B}{\Delta P_o} = \frac{\dfrac{\Delta P_D}{\Delta P_o} A_B}{1 + \dfrac{S}{1000}} = \frac{-0.88}{1 + \dfrac{S}{1000}} \text{ pounds per square inch}$$

where $\Delta P_D / \Delta P_o$ = gain of the amplifier

A_B = effective bellows area

ΔF_B = net force applied to the flapper by the bellows.

2.5 FEEDBACK TRANSDUCERS

The concept developed for the feedback transducer is shown schematically in Figure 2-7. The transducer generates a pneumatic position signal by means of a pneumatic bridge circuit. The output signal is a pressure difference created by motion of the flapper (Figure 2-8) which is driven by the ramp connected to the actuator. The output from the bridge is fed to an amplifier as illustrated in Figure 2-7. Thus a discrete position of the actuator is represented by a certain pressure difference, ΔP_C, at the control ports of the amplifier. At mid-stroke the bridge is nulled and $\Delta P_C = 0$. The motion reduction provided by the lever arrangement of the flapper and follower was used for practical considerations because of the relatively small displacement required at the flapper nozzles. Otherwise, it may have been practical to directly vary the nozzle area with the ramp.

The sizing of the pneumatic bridge was dictated primarily by the input requirements of the feedback amplifier. Operating conditions used for the amplifier are:

Local ambient pressure, P_a = 26 psia

Amplifier supply pressure P_{SA} = 36 psia
    (nozzle drop ΔP_S = 10 psig)

Power nozzle size = 0.010 inch x 0.010 inch

Control port quiescent level, P_{CO} = 29 psia

Saturation signal, ΔP_{CM} = 1 psi
(10 percent ΔP_S)

2-13

Figure 2-7. Schematic Diagram of Feedback Transducer

A_{no} = quiescent A_n

= $\pi\ D_n y_o$

Figure 2-8. Pneumatic Bridge Network.

Power nozzle weight flow W_S = 3.17 x 10^{-5} pounds per second
(H_2 at - 250F)

Quiescent control port flow W_{CO} = 0.475 x 10^{-5} pounds per second
(W_{CO} = 0.15 W_S)

The requirements for the pneumatic bridge to drive the amplifier are to pro-
vide a $\pm$ 1 psig output signal at a level of 29 psia for maximum actuator stroke
($\pm$ 1.5 inches) with good linearity.

The usual method of providing good linearity and a small output signal
(relative to the bridge supply pressure) is to use only small deflections of the
flapper around midposition. This approach was investigated and rejected
because of the resulting very small flapper deflections corresponding to full
actuator travel or because of large quiescent flows required to alleviate this
problem.

The approach concluded to be more practical for this application is to
operate the bridge with the quiescent pressure level, P_{CO}, about equal to
the bridge supply pressure, P_{SF}. In the following computations the control
flow to the amplifier was made small compared to the nozzle flow, W_2, (Figure 2-8).
Thus

$$W_1 = 5.6 \times 10^{-5} \text{ pounds per second}$$

and

$$W_1 \cong W_2$$

At the chosen operating level

$$P_{CO} = 0.985 \ P_{SF}$$

or

$$P_{SF} = 29.5 \text{ psia}$$

At this operating point, the flapper flow area, A_n, is 0.25 A_1; flow in A_1
is subsonic and flow from A_n is choked. Standard pneumatic control relations
(e.g. Ref. 2-3) were used to compute

$$\Delta P_C = f(y)$$

for the chosen operating point and assuming $W_1 = W_2$. The resulting curve has excellent linearity (Figure 2-9). The maximum signal from the bridge (corresponding to maximum actuator travel) is

$$\Delta P_{CM} = 0.05 \, P_{SF} = 0.05 \, (29.5) = 1.5 \text{ psi}$$

This value for the maximum pressure signal can be adjusted to the exact saturation value for the amplifier by: 1) providing pressure drop across relatively large restrictors in the control ports; 2) raising the quiescent level in the pneumatic bridge; or 3) using only the required portion of the stroke of the flapper. Although the quiescent level in the bridge is very nearly equal to the supply pressure, P_{SF}, moderate changes in supply pressure resulting in corresponding quiescent level changes are not serious since amplifier performance is not particularly sensitive to changes in control pressure level (e.g. Ref. 2-1

Sizing of the orifices can now be carried out as follows: A_{no} is determined from the weight flow, W_n, and the upstream pressure, P_{C1}, under choked flow and null conditions, i.e.

$$A_{no} = 2.50 \times 10^{-4} \text{ square inch}$$

for hydrogen at -250F

$$P_{C1} = 29 \text{ psia}$$

$W_n = 7.0 \times 10^{-5}$ pounds per second
(choked flow)

To compute y_o and D_N

$$A_{no} = \pi D_n y_o$$

In order to provide good linearity from the flapper nozzle

$$D_n \geq 10 \, y_o$$

Thus

$$A_{no} = \pi 10 \, y_o^2 = 2.50 \times 10^{-4} \text{ square inches}$$

Ref. 2-3. Blackburn, J. F., Reethof G., and Shearer, J. L., Fluid Power Control, Technology Press., MIT and J. Wiley & Son.

$$P_{CO} = 0.985 \, P_{SF}$$

$$A_{no} = 0.25 \, A_1$$
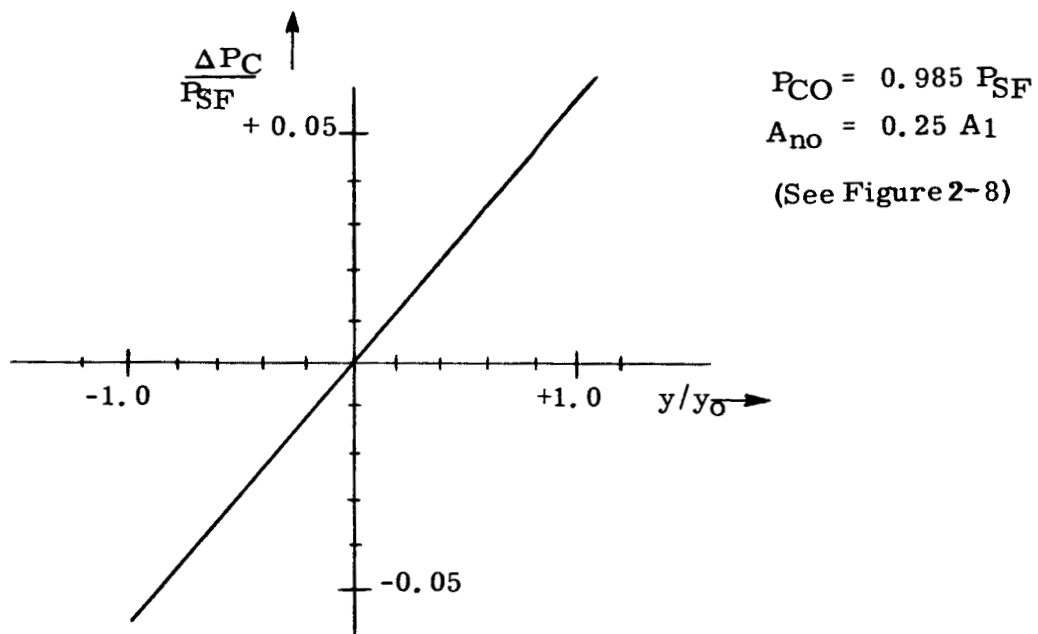
(See Figure 2-8)

Figure 2-9. ΔP_C versus y for Pneumatic Bridge.

Typical Outline

Amplifier Schematic
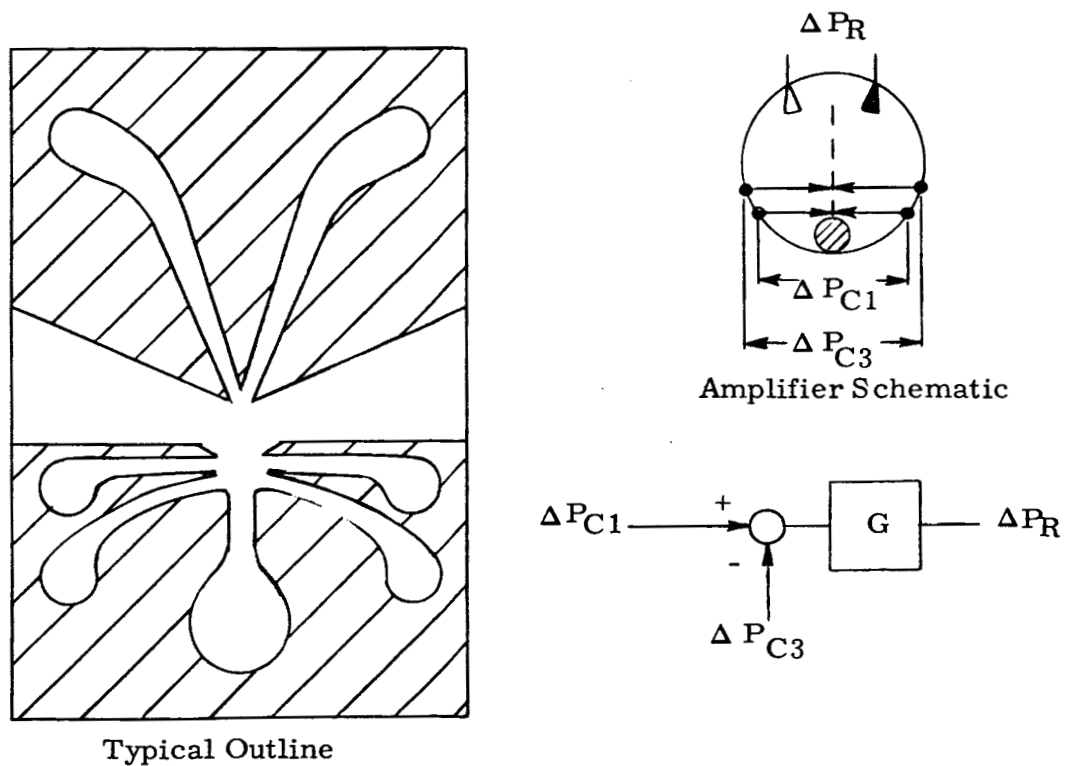
Figure 2-10.   Outline of a Summing Amplifier.

$$y_o = 0.0028 \text{ inch}$$

$$D_n = 10 \, y_o = 0.028 \text{ inch}$$

The size of the upstream restrictor, A_1, is

$$A_{no} = 0.28 \, A_1$$

$$A_1 = 8.93 \times 10^{-4} \text{ square inch}$$

$$D_n = 0.034 \text{ inch}$$

The lever ratio, ℓ_2/ℓ_1, (Figure 2-7) may be limited to about 10 from practical considerations which would result in ramp displacement of ± 0.025 inch for ± 1.5 inches travel.

Gain of the position sensor now can be easily determined. The gain, defined as the change in pressure at the amplifier control ports resulting from a change in position of the actuator, is

$$\frac{\Delta P_C}{\Delta X} = \frac{1.0 \text{ psi (saturation value)}}{1.5 \text{ inches (maximum actuator stroke)}} = 0.67 \text{ psi per inch}$$

Saturation values can be used to determine gain since the sensor is linear throughout its operating range.

In summary, the characteristics of the position sensor are:

Gain = 0.67 psi per inch

Power consumption = 11.2×10^{-5} pounds per second (two nozzles)

$P_{SF} = 29.5 \text{ psia}$

Maximum output, $\Delta P_{CM} = 1.5 \text{ psi}$

Quiescent level, $P_{CO} = 29 \text{ psia}$

$y_o = 0.0025 \text{ inch}$

$D_n = 0.028$

$D_1 = 0.034$

2.6 SIGNAL SUMMATION

Summation of the command and feedback signals is accomplished with a summer amplifier (Figure 2-10). The two differential signals to be summed are applied at the two sets of control ports. The deflection of the fluid jet, or beam, is approximately proportional to the algebraic sum of the two signals. With proper polarity connections, this amplifier provides an output signal, ΔP_R, which is proportional to the difference in input signals, ΔP_{C1} and ΔP_{C3}, (Figure 2-10).

The amplifier operates with a 10 psi power nozzle drop at an ambient pressure of 30 psia. The power nozzle size is 0.010 inch by 0.010 inch which results in a gas consumption of 3.43×10^{-5} pounds per second. Gain for the summer amplifier was assumed to be 4.5 psi/psi.

2.7 LOOP GAIN REQUIREMENTS

From Figure 2-2, the gain requirement for actuator force as a function of load position for the conventional gas servo system is

$$HK_A K_P T_3 A = 500,000 \text{ pounds per inch}$$

The constant K_P is a combination of the torque motor gradient, K_T, and the valve gain, K_2, so that the above gain requirement can be rewritten as

$$HK_A K_T K_2 T_3 A = 500,000 \text{ pounds per inch}$$

The portion of the loop to be implemented with fluid amplifiers will involve component gains from the load to the flapper on the servovalve. The numerical value for this gain is found as follows

$$HK_A K_T = \frac{HK_A K_T K_2 T_3 A}{K_2 T_3 A} = \frac{500,000 \text{ lbs/in}}{200 \times 52.5 \times 0.5} = 95.3 \text{ pounds per inch}$$

Where the numerical values ($K_2 T_3$ and A) for the servovalve and the actuator were determined from Ref. 2-2 to be

$$K_2 = 200 \text{ psi per pound}$$

$$A = 52.5 \text{ square inches}$$

$$T_3 = 0.5 \text{ second}$$

Thus, the fluid amplifiers incorporated into the circuit thus far and their gains are as follows:

Feedback transducer	=	0.67 psi/inch
Feedback amplifier	=	3.6 psi/psi
Summer	=	4.5 psi/psi
Lead-lag	=	0.311 psi/psi
Driver amplifier	=	0.88 pound per psi

Total gain of these blocks is about three pounds per inch, an additional gain of about 33 is needed to produce the required gain of 100 pounds per inch. Staged amplifiers can produce gains from 3.5 to 5.5. Therefore, 2 to 3 additional stages of amplification are required. The amplifiers considered would have power nozzle dimensions of 0.010 inch by 0.010 inch and would operate at 36 psia ambient with a 10 psi power nozzle pressure drop. Gas consumption for each nozzle would be 3.78×10^{-5} pounds per second. A detailed schematic of the final circuit is illustrated in Figure 2-11, and Table 2-1 summarizes the characteristics of the components.

TABLE 2-1

COMPONENT CHARACTERISTICS

COMPONENT	TRANSFER FUNCTION	GAS CONSUMPTION
Feedback Transducer	0.67 psi/inch	11.20×10^{-5} lbs/sec
Feedback Amplifier	3.6 psi/psi	3.17×10^{-5}
Summer	4.5 psi/psi	3.43×10^{-5}
Lead-Lag	$0.311 \dfrac{(1 + \frac{S}{20})}{1 + \frac{S}{290}}$	7.56×10^{-5}
Amplifiers	32 psi/psi	7.56×10^{-5}
Driver Amplifier	$\dfrac{0.88}{(1 + \frac{S}{1000})}$ pounds per/psi	7.60×10^{-5}
		4.05×10^{-4} lbs/sec
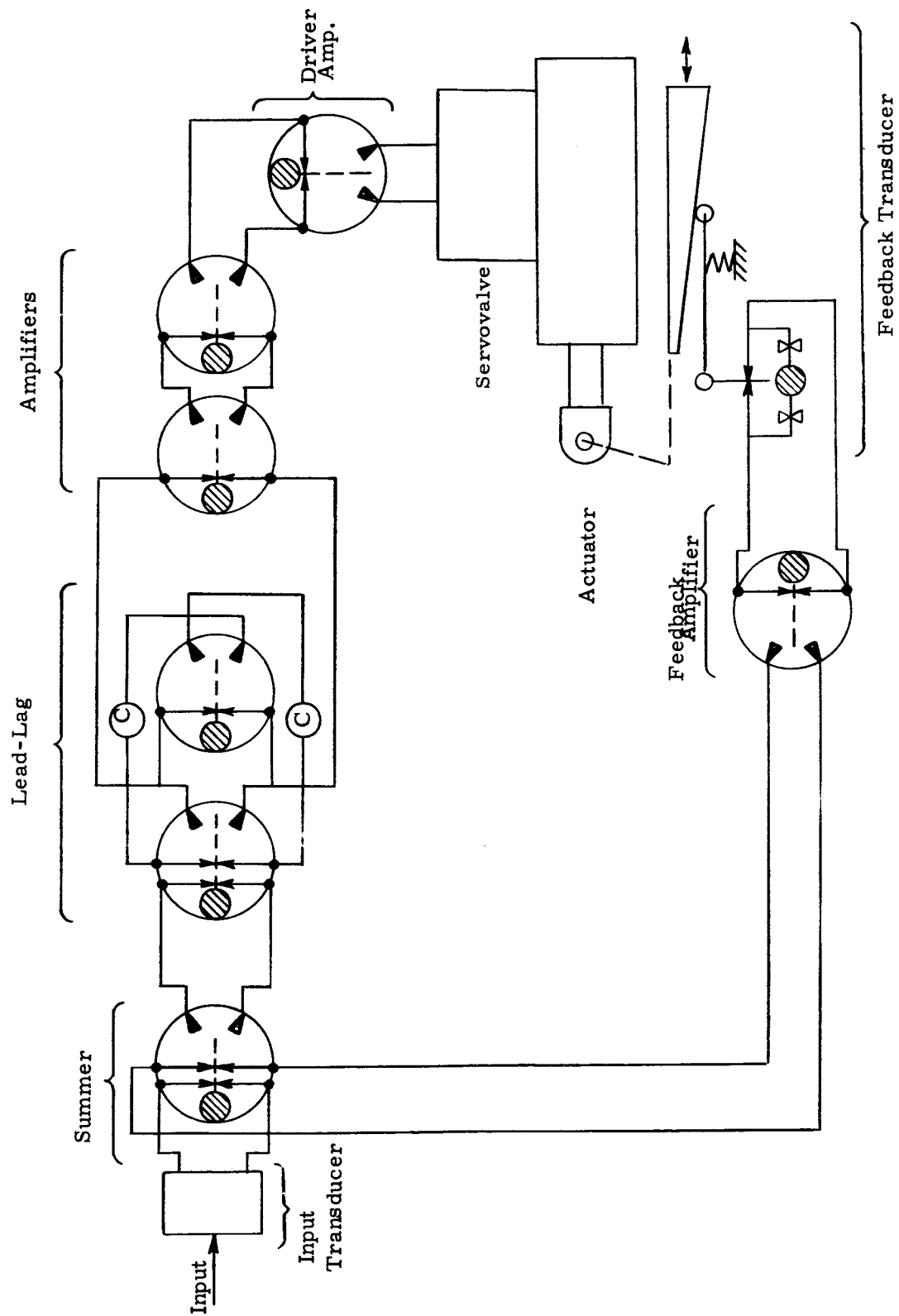
Figure 2-11. Schematic Diagram of Engine Actuator System.

An input transducer (Figure 2-11) is required to convert the electrical command signal into a pneumatic signal. One possible concept for this device is the use of a torque motor and a pneumatic bridge (similar to that used in the feedback transducer). The torque motor could be quite small since the force requirements would be very low. Another possible concept is the use of a piezoelectric material to provide the electro-mechanical conversion. This area may require further investigation to result in the optimum transducer.

Section 3

SPACE STATION LIFEBOAT

3.1 SUMMARY

A space station lifeboat is a small escape vehicle attached to a larger orbiting station. In order to be practical, the lifeboat must be capable of re-entry and landing within a predesignated area. The system must have very high reliability after extended periods of non-use. In addition, it should be capable of operation after exposure to nuclear radiation. Such exposure might occur if the space station inadvertently travels through a high radiation zone, or if, through some mishap, radiation is received from a nuclear reactor onboard the space station.

It will be difficult for the guidance and control system to meet these requirements if they are implemented with conventional space components and techniques. With the use of fluid amplifiers, however, it appears that the requirements could be met. Fluid amplifiers appear to have the required high reliability and long shelf life. Their tolerance to both nuclear and electro-magnetic radiation appears excellent.

The guidance and control system for the lifeboat will be a minimal system since the vehicle would be used only in the event of emergencies. In order to simplify the system, it will depend on the main computer in the space station for present-position information. Some initial manual control by a pilot is also used for simplification. In order to study the application of fluid amplifiers to this general type of re-entry control, a study of the lifeboat mission was necessary to define the guidance and control requirements. Fluid amplifier implementation of the computer and control functions then were investigated. The major conclusions drawn from these studies are:

1. The vehicle to be used as the lifeboat should have lifting capability with maximum lift-to-drag ratio (L/D) of approximately one at hypersonic velocities.

2. Due to the space environment and required operating conditions of the lifeboat, fluid logic equipment will offer distinct advantages over conventional equipment and should be used in mechanizing the complete re-entry control system for the vehicle.

3. Two control systems are considered in this study: 1) a "minimum" system which utilizes orbital plane rotation for cross-range capability; and 2) a complete, self-contained "maximum" system which achieves cross-range capability by means of atmospheric maneuvering. The "minimum" system requires additional equipment for providing the thrust for orbital plane rotation. The "maximum" system has the advantage of continuous corrective capability while in the atmosphere but requires a larger computer. The memory capacity for the "maximum" computer is 1500 ten-bit words versus 700 for the "minimum" system. Both require a cyclic computation rate of 100 iterations per second.

4. The fluid logic re-entry control system will require the development of the following key fluid logic devices:

   a. Digital Integrator -- For use in the system computer and for obtaining velocity and range information. Detail circuits on one possible implementation of a digital integrator are described in Section 4.

   b. Linear Accelerometer -- For measuring vehicle deceleration in the atmosphere to the accuracy of 10^{-3} to 10^{-4} g's.

   c. Attitude Reference -- For use in the attitude control system and for orientating the accelerometers to the accuracy of one to two degrees.

   d. Data Link Between Space Station and Lifeboat -- For reading initial conditions of velocity and range into the fluid logic computer.

e. Skin Temperature Sensor (Optional) -- For measuring skin temperature and providing temperature control for the vehicle during re-entry.

5. The components of the fluid logic re-entry control system must meet the following accuracy specifications for successful operation:

Component		Accuracy
a)	Linear accelerometer -	0.5×10^{-3} g's
b)	Attitude reference -	± 1.5 degrees
c)	Skin temperature sensor -	$\pm 50F$
d)	Attitude rate gyro null shift -	0.1 - 0.5 degrees per hour (threshold)
e)	Digital integrator drift -	1 part per 1000 per hour

6. The "Power On" time for the fluid logic system will be from 20 to 30 minutes, depending on range requirements. During this time the system will have the following power requirements:

MINIMUM SYSTEM

Component	Power Requirements (Watts)
Computer (including interface)	12.6 (6300 elements with a 0.1 psi 10 x 10 mil nozzle)
Rate gyro (1)	0.2
Accelerometers (2)	0.4
Auxiliary equipment	0.5
Actuation system (reaction jet in orbit and boundary layer control in atmosphere)	Undetermined
Total	13.7 Watts (less actuation system)

MAXIMUM SYSTEM

Component	Power Requirements (Watts)
Computer	26.8 (13,400 elements with a 0.1 psi 10 x 10 mil nozzle)

Component	Power Requirements
Rate gyros (2)	0. 4
Accelerometers (3)	0. 6
Auxiliary equipment	1. 0
Actuation system (reaction jet in orbit and boundary layer control in atmosphere)	Undetermined
Total	28. 8 Watts (less actuation system)

3.2   SYSTEM DESCRIPTION

3.2.1   VEHICLE SELECTION

The guidance and control system, commonly referred to as the Energy Management System, computes and commands the maneuvers required for re-entry. For this type of vehicle, the system must meet the following objectives:

1.   Land the space lifeboat within a specified radius (approximately 50 to 100 miles) of the designated landing area.

2.   Have the capability to land at one of several acceptable landing areas at any time during orbit.

3.   Have a maximum error-correcting capability in order to allow for errors in the deorbiting sequence and subsequent atmospheric maneuvers.

4.   Re-enter with relatively low g loading on the occupants.

5.   Provide for a maximum of safety for the occupants during re-entry.

Due to the nature of the mission and the small size of the vehicle, alignment for retro fire and retro fire will be done by the pilot. Errors in the retro-fire sequence introduced by the pilot will result in range errors at re-entry and also errors in the re-entry angle (the angle at which the flight path intersects the atmosphere).

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* See Section 10 for definition of pneumatic power.

If the space lifeboat is a ballistic vehicle, it must depend entirely on the accuracy and timing with which the pilot fires the retro rocket to obtain the desired range. Its atmospheric maneuvering capability is essentially negligible, and the atmospheric range is governed by the re-entry angle. Furthermore, since atmospheric range is governed by the re-entry angle, relatively large g loading can occur if a short range is desired (large re-entry angle). High g loads will be experienced, especially if an error is made in the retro-fire sequence while attempting to attain this steep re-entry angle.

As a result, with the occupant safety and range maneuvering requirements of prime importance, a re-entry vehicle having lifting capability is dictated. A typical lifting vehicle representative of the vehicle considered in this study is shown in Figure 3-1.
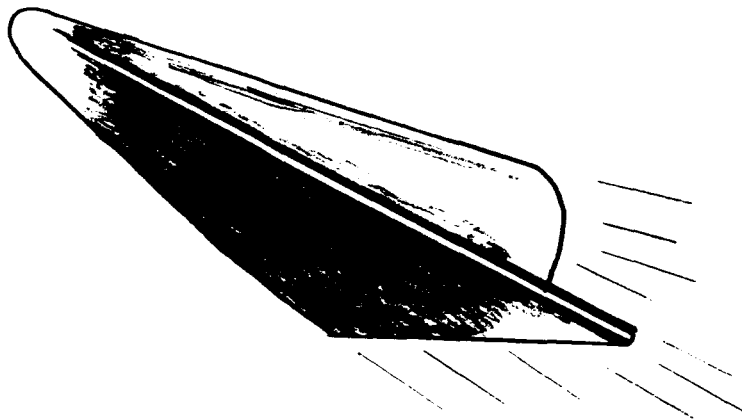
Figure 3-1.
Proposed Vehicle
Configuration for
Space Lifeboat.

This vehicle would be a modified version of the current U.S. Air Force ASSET (Aerothermodynamic Structural Systems Evaluation Test) vehicle having a maximum lift-to-drag ratio (L/D) of unity at hypersonic velocities.

3.2.2 GUIDANCE AND CONTROL

The techniques for the guidance and control of the space lifeboat have been developed by the General Electric Company on the following U.S. Air Force contracts:

1. "Study of Advanced Energy Management Techniques", ASD TDR 62-77, Volumes I and II, June 1962, Contract AF33(616)-7936.

2.   "Analog/Digital Simulation and Study of a Dynamic Energy Management System", ASD TDR 63-, October 1963, Contract AF33(657)-8433.

A generalized block diagram of the guidance and control system (Energy Management) is shown in Figure 3-2. The guidance and control computer, using position information from the navigation system, predicts while in orbit the range capability of the vehicle as well as the range to the nearest acceptable landing area. Assuming the destination is within the range capability of the vehicle, it then predicts the path which must be flown to land the vehicle at its destination. Upon orbit ejection by retro-thrust, the computer computes the control commands to fly the predicted path using information provided by the navigation system and the sensors. As the flight progresses, the computer continually updates the predicted path to assure convergence on the landing area.

System operation begins at separation from the space station, at which time the current re-entry data is read into the guidance and control computer on board the space lifeboat. The pilot, using manual control, orientates the vehicle for retro-fire as soon as possible after separation from the mother ship. To minimize equipment, visual orientation with the horizon (similar to that used in the Mercury series) will be used.

The orbital range covered to re-entry is very sensitive to the angle (β) at which the retro is fired in respect to the velocity vector as shown in Figure 3-3. To minimize this effect, an angle of approximately 22 degrees (β_{opt}) is used. Upon firing the retro, the vehicle is put in a transfer orbit as shown in Figure 3-4. This orbit is governed by the retro-thrust (ΔV) and the firing angle β (in this case 22°), and it is designed to intersect the atmosphere at a re-entry angle, γ_{re}, half way between the maximum allowable and the minimum allowable. The maximum angle is determined by the heating and/or deceleration limitation of the vehicle and its passengers. The minimum angle is governed by the skipping limitation. By using a median re-entry angle, maximum flexibility in the retro-fire sequence is factored in without sacrificing the safety of the vehicle and its occupants..

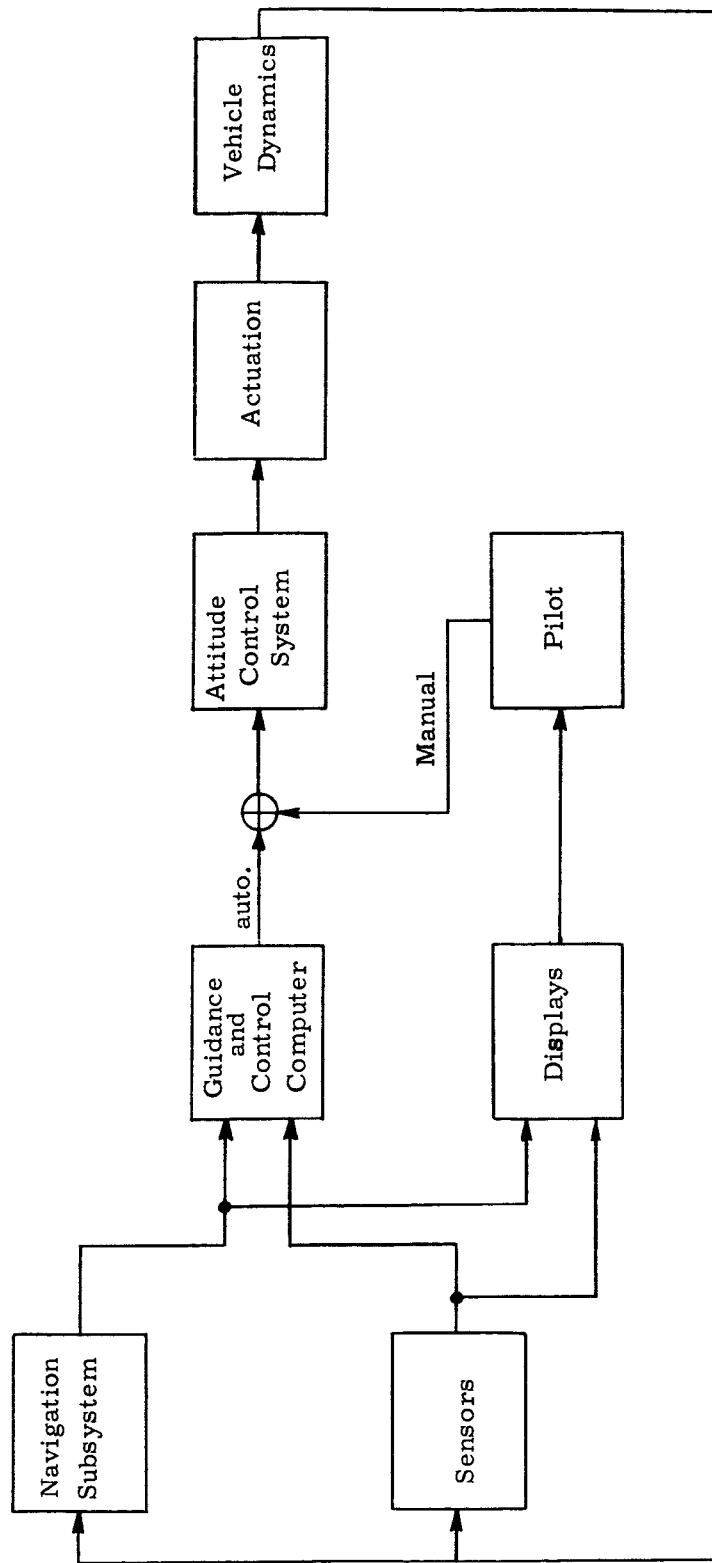Figure 3-2. Generalized Block Diagram of Guidance and Control System for the Space Lifeboat.
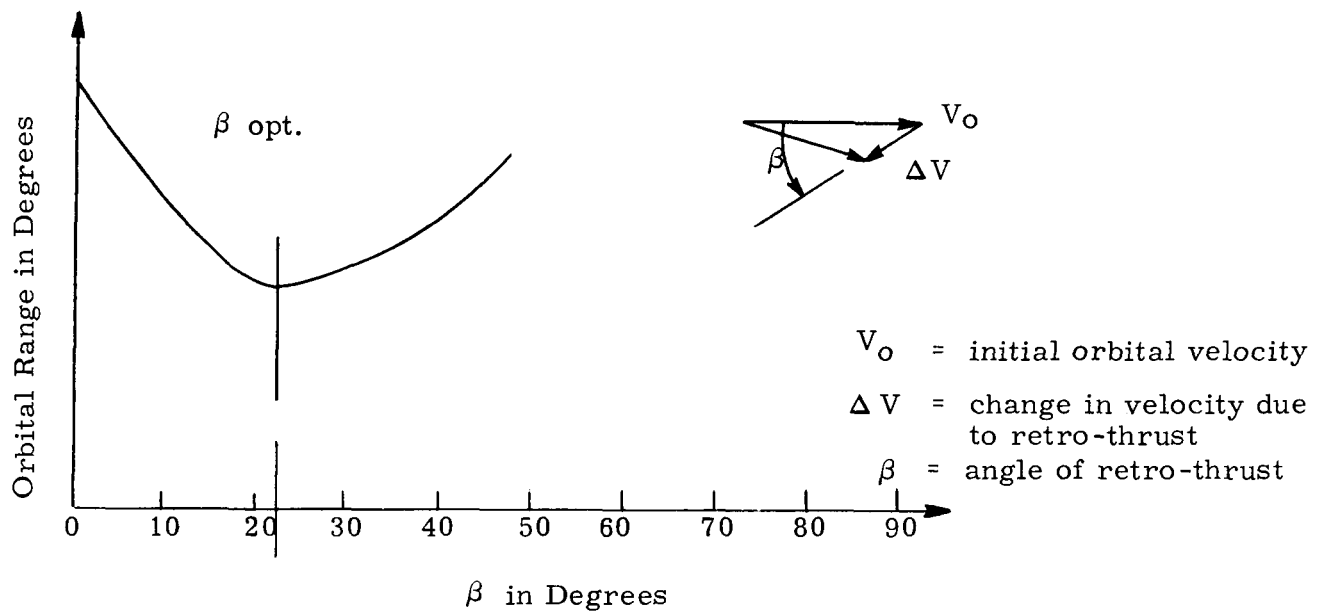
Figure 3-3. Orbital Range as a Function of Retro-Fire Angle β

V$_o$ = initial orbit velocity

ΔV = retro-thrust

β = retro-thrust angle

γ_{re} = re-entry angle

R$_o$ = initial orbit radius
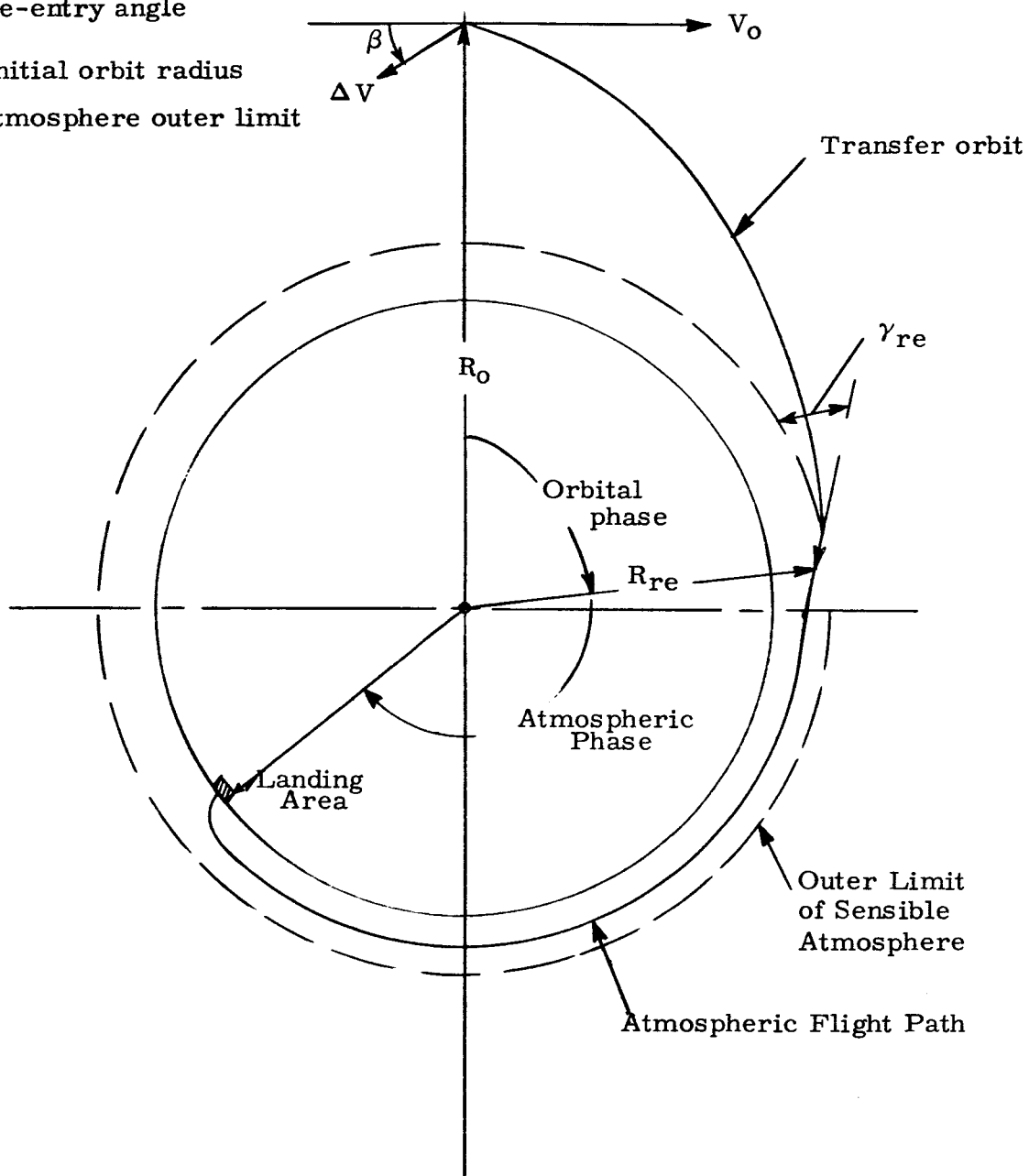
R$_{re}$ = atmosphere outer limit

Figure 3-4. Re-entry Profile for the Space Lifeboat.

Re-entry into the atmosphere will be accomplished at a maximum angle of attack in order to obtain maximum drag. Due to the mechanics of the transfer orbit and the lift provided by the aerodynamic force encountered, the vehicle will level off (vertical velocity = 0) after entering the atmosphere. At this point, the velocity will be below the satellite velocity* (i.e. 25782 f.p.s.) and immediate equilibrium glide will be initiated at an angle of attack providing an L/D compatible with the conditions attained. As the velocity decreases, the path-control system will gradually change the angle of attack until the desired L/D is attained which is predicted by the computer for guiding the vehicle to the landing area.

The vehicle continues flying the predicted path until the velocity decreases to approximately 1000 f.p.s., and an altitude of 60,000 to 80,000 feet is reached. At this point a first drogue chute is deployed to slow the vehicle descent velocity. At approximately 30,000 feet a second drogue chute is deployed, and at approximately 15,000 to 20,000 feet a large chute is deployed for landing.

3.2.3 CROSS-RANGE CAPACITY

For this type of vehicle, cross-range is attainable by two means: 1) Orbital plane rotation; and 2) Atmospheric maneuvering.

Orbital plane rotation is attained by firing the retro rocket in the tangential plane such that a thrust perpendicular to the plane of the initial orbit is attained. While quite effective, the amount of retro required can be prohibitive in order

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*This criterion will set the minimum allowable re-entry angle for a particular initial orbit.

to attain significant cross-range. However, if the fuel for the retro is available from the space station this may not be a constraint. Another disadvantage to this approach is that it is a "one-shot" approach, allowing for no further corrective action unless additional retro-thrust is available.

Atmospheric maneuvering is attainable by utilizing the lifting capability of the vehicle by means of banking. It has continuous corrective capability and therefore has a distinctive advantage over the orbital cross-range maneuver in this respect. It also requires no additional energy storage on the vehicle. It does, however, require the addition of another measurement axis in the navigation system, an increase in computation requirements on the computer, and another axis of control in the attitude control system and the actuation system.

3.2.4 MISSION TIMES

The total re-entry time from separation to landing will be in the order of 40 to 60 minutes, but the system will be in the "power-on" condition only 20 to 30 minutes. Five to 10 minutes of this "power-on" time will be used in the retro-fire sequence and will require only sufficient power for manual attitude control. The remaining time, 15 to 20 minutes, will be in the atmosphere and will require "power-on" operating conditions.

3.3 SYSTEM MECHANIZATION

The approach used in mechanizing the lifeboat control system was to establish a minimal computer to adequately perform the required functions. This approach results in the least complex fluid circuitry, thus providing the highest reliability and minimum power consumption. A minimal system results if much of the initial guidance computations (i.e. computation of orbital transfer and range to landing areas from present position in orbit) is done on the mother ship and continuously fed into the space lifeboat.

To further minimize the computational and system requirements, a "minimum" system can be defined that will control only the down-range of the

vehicle while in the atmosphere. The necessary cross-range will be attained by orbital plane rotation using retro thrust as explained previously. This "minimum" system will provide a building block that can be expanded upon to provide, eventually, full operating capability.

Based on the re-entry control techniques developed in the previously mentioned U.S. Air Force Contracts, the guidance and control system for the lifeboat using fluid amplifiers and logic mechanization is as shown in Figure 3-5. In this diagram, the interfaces in the computer represent points of data transmission. If all computation is on board the lifeboat, interface "1" represents the point at which data must be transmitted to the guidance and control computer from the mother ship. If the orbital transfer and range calculations are done on the mother ship, interface 1 (alternate) represents the point at which data is transmitted to the lifeboat.

3.3.1 GUIDANCE AND CONTROL COMPUTER

The section between interfaces 1 and 2 (Figure 3-5) represents the guidance and control computer. Assuming that the orbital transfer and range calculations are done on the mother ship, the computer consists of four distinct sections:

1. Control logic -- Organizes the computation cycle, updates the predicted path, and determines the range capability of the vehicle and the corresponding destination attainability.

2. Prediction model -- Computes, in fast time, the vehicle's range for a given angle of attack, as specified by the control logic section.

3. Path control -- Computes the commands to fly the predicted path. In order to insure stability a path control computation is done every time a prediction is made.

4. Display control -- Computes the commands for the pilot display given the range capability and range of the destination by the control logic section
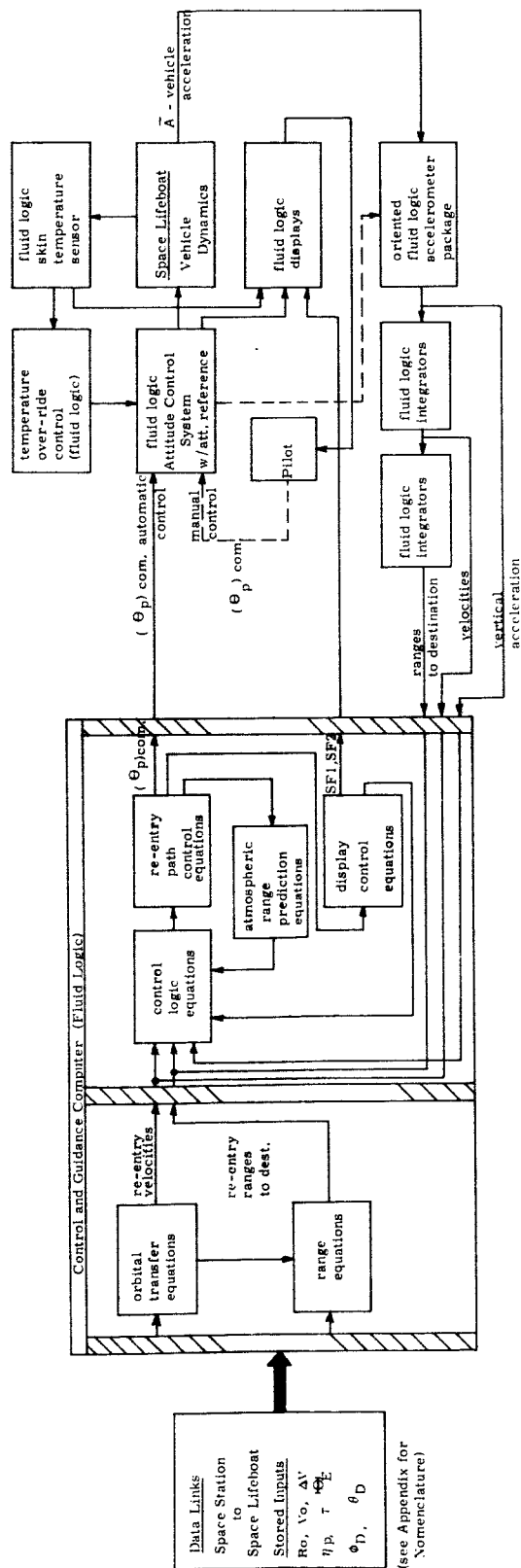
3-12

Figure 3-5. Fluid Logic Guidance and Control System for Space Lifeboat.

For the mission of the lifeboat, the guidance and control equations developed in the previously mentioned U.S. Air Force contracts were modified and simplified in order to determine the computation requirements.

In specifying these equations, the following four basic situations were considered:

Case 1. Minimum system, down-range control only in the atmosphere with orbital and range equations computations not on board.

Case 2. Minimum system, down-range control only in the atmosphere, with orbital and range computations on board.

Case 3. Maximum system, down-range and cross-range control in the atmosphere with orbital and range computations not on board.

Case 4. Maximum system, down-range and cross-range control in the atmosphere with orbital and range computations on board.

For each of these four cases, the implementation required to solve the equations was developed and the memory size, number of digital integrators, and iteration rate were determined. The results are presented in Table 3-1 in terms of 10-bit absolute language instructions or words.
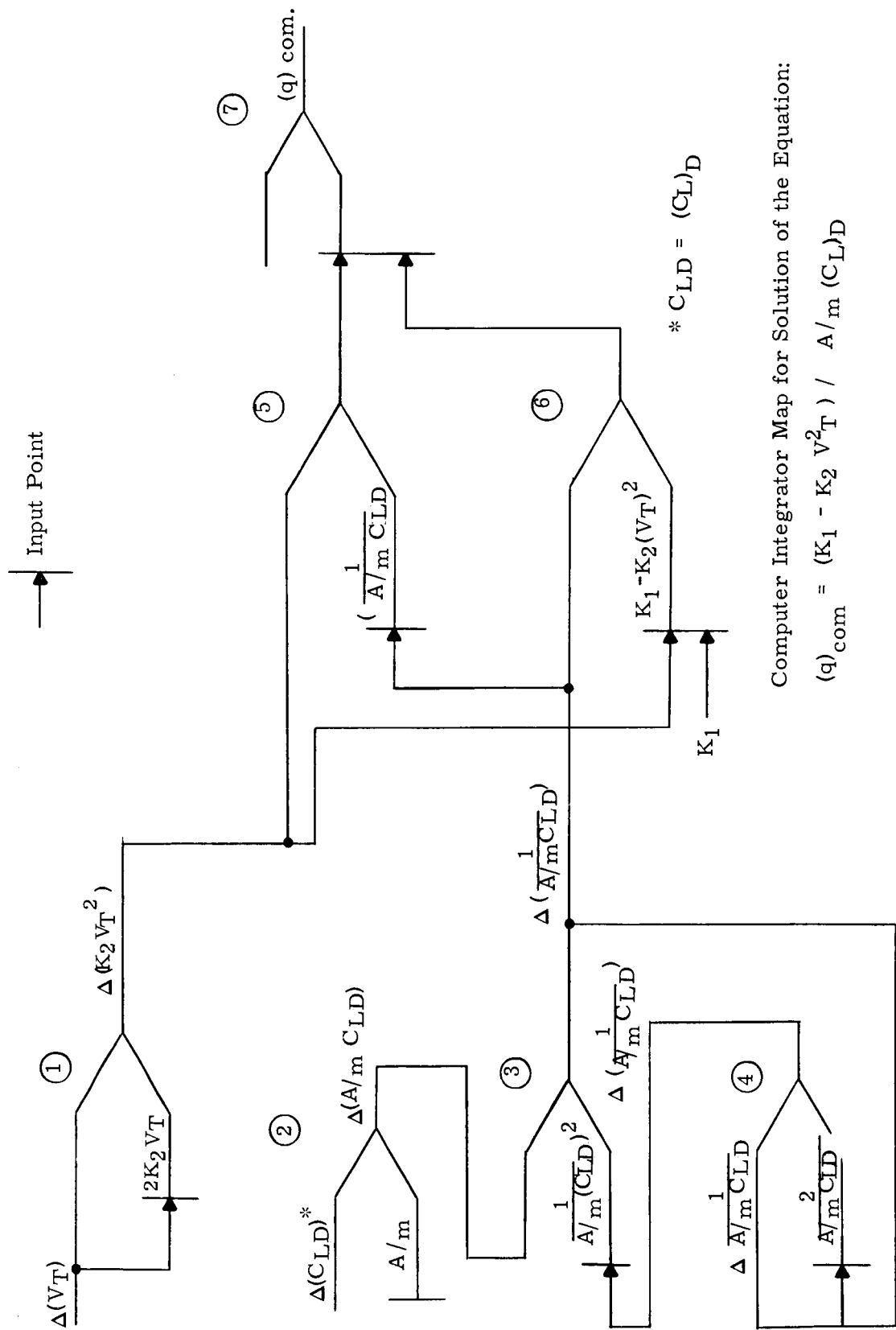
In the actual application, the minimum computer requirements probably can be those of Case 1. The proper development approach would therefore be to mechanize the computer for Case 1 in order to prove feasibility and to determine the actual operating characteristics of the computer itself. As the state-of-the-art progresses, Case 2, 3 and 4 (in that order) could be mechanized to arrive at the ultimate system computer.

The computer, as indicated in Table 3-1 consists primarily of fluid digital integrators interconnected to perform the computations required by the guidance and control equations. The equations required for Case 1 are listed in the paragraph 3.9. An example of how the fluid integrators can be interconnected to perform a desired computation is illustrated by the integrator map shown in Figure 3-6. The equation computed is Eq. (3-75) which is used in the path control section of the computer to determine the desired path command for the

TABLE 3-1

Computer Size and Required Computation Speed for Space Lifeboat Mission

Case	Memory Size 10 Bit Absolute Machine Words			Fluid Logic Hardware (Digital Integrators)	Computation Rate (Iterations/second)
	Main-Line	Sub-Routines			
1	352	316	668	64	100
2	714	462	1176	115	100
3	603	479	1082	105	100
4	945	525	1470	140	100

Figure 3-6. Typical Computer Implementation with Digital Integrators.

Computer Integrator Map for Solution of the Equation:

$$(q)_{com} = (K_1 - K_2 V_T^2) / A/m (C_L)_D$$

$* C_{LD} = (C_L)_D$

L/D desired. This equation is:

$$(q)_{com} = (K_1 - K_2 V_T^2) / (C_L)_o \, A/m$$

where:

$(q)_{com}$ - Dynamic pressure command (lb/ft^2)

V_T - Tangential velocity (ft/sec)

$(C_L)_o$ - Desired lift coefficient as related to desired L/D

A/m - Area to mass ratio of vehicle $(ft^3/lb\text{-}sec^2)$

K_1 - 31.42

K_2 - 4.72×10^{-8}

In Figure 3-6, specific integrators are identified by the circled numbers opposite each of the integrator symbols. The inputs to the integrators are increments of the variables involved and are represented by pulse rates. The lower input represents the integral or dependent variable and the upper input the independent variable.

Each integrator performs the operation:

$$\int y \, dx = \sum_{i=1}^{n} Y_i \, \Delta x_i$$

where:

Y_i = the dependent variable

Δx_i = the independent variable

Integrator ① performs the multiplication of $2 K_2 V_T$ by the variable ΔV_T to obtain $\Delta K_2 V_T^2$, the factor of two being a scale factor. Integrator ② multiplies the constant A/m by $(C_L)_D$. Integrators 3 and 4 generate the reciprocal of $A/m (C_L)_D$. Integrators ⑤ and ⑥ generate the incremental product of $(K_1 - K_2 V_T^2)$ and $1/A/m (C_L)_D$. The output of these integrators are then summed into a succeeding integrator ⑦ to obtain $(q)_{com}$.

The constants $(2 K_2)$ and (A/m) in integrators ① and ② are inserted as initial conditions. Constant K_1 is represented by a pulse rate.

A detail description of the digital integrator including circuits is presented in Section 4, "Computation and Logic (Digital Integrator)," of this report.

For the computation times required for system stability, it has been determined that a speed of 100 iterations per second is required. For a 10-bit word, this means that the clock speed required would be 1000 cps. This clock speed and even higher speeds should be attainable in the time period when this computer would be mechanized.

3.3.1.1 Critical Areas

The computer consists of a number of digital integrators, interconnected to perform the required computations. The fluid digital integrator, however, is only in the very initial development stage and further development and tests are required to prove out the device. This is a very critical development and its success will determine the feasibility of the fluid logic re-entry system.

Another critical area is the transmission of data (data link) from the space station to the space lifeboat just prior to separation. A means is required of continuously storing this data such that it is available for the vehicle at separation without requiring power to the computer on board the lifeboat.

3.3.2 ATTITUDE CONTROL SYSTEM

The function of the attitude control system (Figure 3-5) is to control the vehicle such that it attains and maintains a commanded attitude angle (pitch angle θ_P) in the case of longitudinal control. Proper attitude control requires an attitude reference, means of actuation, and a feedback control.

3.3.2.1 Reference

In conventional systems, an attitude gyro provides the proper attitude reference. However, for fluid logic systems no such reference is known with current state-of-the-art techniques.

An approach that appears feasible is to use a fluid attitude rate sensor (which is feasible and under development) and digitally integrate, using a fluid logic integrator, the output of this rate sensor to obtain the change in attitude and add this to the initial attitude angle.

For this approach, the initial attitude angle must be available. While in the orbital phase, this initial angle can be obtained quite accurately by using a sun-sensing technique. A possible approach for sun sensing is the use of an array of bimetallic elements located along the vehicle so that they are exposed to the sun, depending on the attitude of the vehicle. These bimetallic elements, in turn, close or open fluid ports which are used to provide the fluid attitude reference. This approach is only feasible in the orbital phase where the heat of the sun is dominant. In the atmosphere the heating of the vehicle would quickly blot out this reference. For this reason, the integrating approach described previously is proposed for atmospheric attitude control with the sun-sensing technique being used to provide the initial attitude fix just prior to atmospheric re-entry. The sun-sensing attitude reference might also be used by the pilot to align the vehicle for retro fire.

The accuracy of the sun-sensing attitude measurement technique is estimated to be less than 0.1 degree. However, the accuracy of the rate sensor-integrator technique will depend heavily on the null shift of the attitude rate sensor and inherent drift of the integrator. At this time, a preliminary estimate would be that accuracies of about one to two degrees could be expected throughout the atmospheric flight of the vehicle, which for this type of re-entry system is considered to be adequate.

3.3.2.2 Actuation

The control force required to orientate the vehicle while in orbit or the high atmosphere, i.e., above 200,000 feet, can be obtained by reaction jets. The power required for the reaction jets can be the actual fluid used by re-entry system itself and, therefore, is particularly adaptable to fluid logic control.

In the lower atmosphere, below 200,000 feet, aerodynamic forces become significant and reaction jets become inefficient and, in this case, another means

of control is required. A conventional means is to use control flaps to effect aerodynamic control, moving the flaps by control actuators. An alternative means, requiring no external control, is to shift the relative center of gravity of the vehicle thereby providing rotation in the desired plane. Shifting of the center of gravity can be effected by moving a mass within the vehicle, such as pumping a fluid to a new location. A similar type control is proposed for the Apollo re-entry capsule. Fluid logic should be adaptable to this means of control more readily than to control flaps since this shift of the center of gravity could be done without moving parts.

A technique using boundary layer control has also been conceived at the General Electric Company and appears promising for this application. By controlling points of separation of the boundary layers the vehicle can be oriented in desired attitudes. This boundary layer control can be achieved through fluid injection-aspiration techniques and appears particularly adaptable to fluid logic control. The technique of control, however, is still in the research stage and more development work must be done before any further conclusions as to its practicality can be drawn.

3.3.2.3 Feedback Control

Due to the large change in the magnitude of the control variables from orbit through re-entry, some form of feedback gain changing (adaptive control) will be necessary. Since the vehicle is a lifting vehicle, gain changing probably can be done as a function of vehicle velocity since, in equilibrium glide for a given lift coefficient and density profile, altitude can be related directly to velocity. Another variable that can be used is dynamic pressure (q) which is the control variable in the path control system.

Since a fluid logic computer is on board, the feedback control system would probably (although not necessarily) be digital in nature using attitude error and attitude rate for control. Mechanization of the system should not impose any more problems than mechanizing the guidance computer and should increase the size of the computer by about 10 percent.

3.3.3 NAVIGATION -- ACCELERATION, VELOCITY, AND RANGE INFORMATION

While the space lifeboat is attached to the space station, navigation computations will be done by the main computer on board the space station. At separation, the range and velocity information and the time to re-entry from retro are read into the fluid logic computer on board the space lifeboat.

From separation to re-entry no further velocity information is available, and the re-entry velocities and ranges to the destination at re-entry must be used as initial conditions for re-entry navigations.

In the atmosphere, change in velocity and range can be measured by integrating the output of accelerometers which are appropriately orientated*. The orientation of these accelerometers would be controlled by the attitude reference described in 3.3.2.

The accelerometer for this application is a critical element but, at present, some promising approaches exist. One approach is to use a seismic mass in the form of a sphere which is contained within a tube and is held against a position limiter by fluid support. The corresponding flow around the ball centers the device in the tube. When an acceleration is applied, the ball rolls toward one pickoff and away from the other, resulting in a pressure differential. This pressure differential varies directly with acceleration force. This device has already been tested and found satisfactory. Three of these accelerometers orientated along each axis would be required for three axis acceleration measurements.

Another technique, that looks even more attractive, is a device that measures accleration in three axes at once and can be contained in a single unit. It also employs a seismic mass in the form of a sphere which is centered by three pairs of fluid pressure ports, each pair orientated along a sensitive axis. Under acceleration, a differential pressure between a pair of ports is required to keep the mass centered; this differential pressure is directly proportional to the acceleration applied along the respective axis.

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*A fluid timer, set by the "time-to-re-entry" input from the mother ship, would be used to turn on the power for the system and correspondingly for the accelerometers.

To obtain velocity and range information, the output of the accelerometers must be integrated. At present, it appears feasible to convert the analog accelerometer signal to digital and to perform the integration in the computer using the digital integrators. This technique is dependent, as is the fluid logic computer, on the development of the digital integrators.

3.3.4 DISPLAYS

In order to provide capability for manual control for the pilot in the retrofire sequence and possibly for over-ride control by the pilot during re-entry in the case of computer failure, displays of some nature are essential. However, due to the problems of fluid mechanization and space, they must be kept as simple as possible.

The displays considered desirable for this mission are:

1. Attitude
2. Skin temperature
3. Range capability and destination location (optional)

In the case of attitude and temperature, the driving signals are available directly from the attitude reference and temperature sensor respectively. The range capability and destination location, however, must be computed, converted to analog, and fed to the display. The use of this display may be optional and will depend on considerations such as space available and power consumption.

3.4 SKIN TEMPERATURE MEASUREMENT

In order to provide a temperature limit during re-entry, a temperature over-ride control on the attitude command is required, especially when the air flow changes from laminar to turbulent, which results in higher heating rates for a particular set of flight conditions. If, at a certain time, the commanded pitch angle is too high for the heating conditions, the pitch angle command will be limited as a function of the proximity of the temperature limit until the heating condition has been relieved. Or, if banked, the bank angle command will be limited as a function of the proximity to the temperature limit, thereby reducing the pitch angle requirements and relieving the heating condition.

The need therefore exists for a fluid temperature sensor. One approach that has been demonstrated utilizes a fluid oscillator, located in the area in which the temperature is being measured. Heating or cooling of the device will change the speed of sound of the fluid in the device and, hence, the frequency of the oscillator. The frequency of the oscillator then can be calibrated to the temperature sensed and used as the over-ride control signal and to drive the pilot temperature display.

3.5 MANUAL CONTROL

Manual control is essential for retro-fire orientation by the pilot and to provide him manual over-ride control during re-entry. Mechanization of this control appears straightforward using state-of-the-art techniques.

3.6 NOMENCLATURE

A = Effective platform area

$\overline{A}$ = Acceleration

$\overline{A}_V$ = Vertical acceleration

C_L = Lift coefficient

C_D = Drag coefficient

K_1, K_2 = Feedback gains in path control system

L/D = Lift-to-drag ratio

N = Number of re-entry phase

N_P = Quadrant of vehicle location in orbit

R_o = Radius from center of earth to orbit (ft)

R_{Re} = Radius from center of earth to re-entry altitude (ft)

R_C = Cross-range (ft)

R_D = Down-range (ft)

SF_1 = Display seal factor

SF_2 = Display seal factor

t = Time (sec)

$$u \quad = \text{Down-range velocity (ft/sec}^2)$$

$$v \quad = \text{Vertical velocity (ft/sec}^2)$$

$$V \quad = \text{Velocity (ft/sec}^2)$$

$$V_T \quad = \text{Tangential velocity} = \text{(ft/sec}^2)$$

$$W \quad = \text{Cross-range velocity (ft/sec}^2)$$

$$X_D \quad = \text{Down-range desired (ft)}$$

$$Y_D \quad = \text{Cross-range desired (ft)}$$

$$\alpha \quad = \text{Angle of attack (deg)}$$

$$\beta \quad = \text{Angle of retro-fire in the orbital plane in respect to the velocity vector (deg)}$$

$$\gamma \quad = \text{Path angle (deg)}$$

$$\eta \quad = \text{Angle of rotation in plane of orbit (deg)}$$

$$\Theta \quad = \text{Longitude at which the orbital plane intersects the equator -- measured eastward from Greenwich Meridian (deg)}$$

$$\theta \quad = \text{Longitude measured eastward from Greenwich Meridian}$$

$$\phi \quad = \text{Latitude measured positively Northward from equator}$$

$$\Delta V \quad = \text{Retro-thrust (ft/sec}^2)$$

Subscripts

A, C	Refers to phase of re-entry
$(\quad)_{com}$	Commanded value
$(\quad)_{\theta}$	Desired value
D, T	Refers to destination
P	Refers to present position

3.7 COMPUTER EQUATIONS

3.7.1 ORBITAL RE-ENTRY EQUATIONS * (NO ORBITAL PLANE ROTATION)

$$K^2 = 1 + \left(\frac{\Delta V}{V_o}\right)^2 - 2\left(\frac{\Delta V}{V_o}\right) \cos \beta \qquad (3\text{-}1)$$

$$Z = R_o / R_{Re} \qquad (3\text{-}2)$$

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* The orbital re-entry equations were originally derived by J. Carroll, Consultant, Re-entry Systems Department, General Electric Company, Philadelphia, Pa.

$$C = 2 - K^2 + \left(\frac{\Delta V}{V_o}\right)^2 \sin^2 \beta \tag{3-3}$$

$$v_{Re} = -V_o \sqrt{(-K^2 z + 2z - C)} \tag{3-4}$$

$$V_{Re} = V_o \sqrt{K^2 + 2(z - 1)} \tag{3-5}$$

$$\theta_{Re} = \left\{ \sin^{-1}\left(\frac{K^2 z - 1}{\sqrt{1 - K^2 C}}\right) - \sin^{-1}\left(\frac{K^2 - 1}{\sqrt{1 - K^2 C}}\right) \right\} \tag{3-6}$$

$$T_{RC} = \frac{R_o}{C V_o} \left\{ \frac{\sqrt{(-K^2 z + 2z - C)}}{z} - \sqrt{(-K^2 + 2 - C)} \right.$$

$$\left. + \frac{1}{C^{1/2}} \left[\sin^{-1}\left(\frac{z - C}{z\sqrt{1 - K^2 C}}\right) - \sin^{-1}\left(\frac{1 - C}{\sqrt{1 - K^2 C}}\right) \right] \right\} \tag{3-7}$$

3.7.2 RANGE EQUATIONS

$$\eta = \frac{\sin \phi_D}{\cos \tau} \tag{3-8}$$

$$\theta_1 = \Theta_E + \tan^{-1}\left[\tan \eta \sin \tau\right] \tag{3-9}$$

$$\Delta \tau = \sin^{-1}\left[\frac{\tan(\theta_D - \Theta_E)}{\tan \eta}\right] - \tau \tag{3-10}$$

$$\Delta \Theta_E = \theta_D - \theta_1 \tag{3-11}$$

$$\eta_1^1 = \eta - 180^o \tag{3-12}$$

$$\eta_2^1 = \eta - 90^o \tag{3-13}$$

$$R_{C_1} = \sin^{-1}\left[\cos(90^o - \Delta \Theta_E) \cos \eta\right] \tag{3-14}$$

$$R_{C_2} = \sin^{-1}\left[\cos(90^o - \Delta \tau) \cos \eta\right] \tag{3-15}$$

$$R_C = \left[\frac{90^{\circ} - |\eta_1^1|}{90^{\circ}}\right] R_{C_1} + \left[\frac{90^{\circ} - |\eta_2^1|}{90^{\circ}}\right] R_{C_2} \qquad (3\text{-}16)$$

$$\eta_{D_1} = \eta \qquad (3\text{-}17)$$

$$\eta_{D_2} = \sin^{-1}\left[\tan R_C \tan(90^{\circ} - \Delta \tau)\right] \qquad (3\text{-}18)$$

$$\eta_D \left[\frac{90^{\circ} - |\eta_1^1|}{90^{\circ}}\right] \eta_{D_1} + \left[\frac{90^{\circ} - |\eta_2^1|}{90^{\circ}}\right]\eta_{D_2} \qquad (3\text{-}19)$$

$$\eta_D^1 = 90^{\circ} + \eta_D \left\{(\Theta_E + \Delta\Theta_E - \theta_T) > 0\right\} \qquad (3\text{-}20)$$

$$\eta_D^1 = 180^{\circ} - \eta_D\left\{(\Theta_E + \Delta\Theta_E - \theta_T)\right\} > 90^{\circ} \qquad (3\text{-}21)$$

$$\eta_D^1 = 90^{\circ} - \eta_D\left\{(\Theta_E + \Delta\Theta_E - \theta_T)\right\} > 180^{\circ} \qquad (3\text{-}22)$$

$$\eta_D^1 = 180^{\circ} + \eta_D\left\{(\Theta_E + \Delta\Theta_E - \theta_T)\right\} > 270^{\circ} \qquad (3\text{-}23)$$

$$R_D = (N_P + 1) 90^{\circ} - \eta_P + \eta_D^1 \qquad (3\text{-}24)$$

3.7.3 ATMOSPHERIC CONTROL EQUATIONS (FORTRAN FORMAT)

3.7.3.1 Control Logic Equations

20 go to (30, 40, 50, 60, 70), NDX $\qquad (3\text{-}25)$

30 $ND_x = 2$ $\qquad (3\text{-}26)$

$\alpha_{AA} = (\alpha_A)_{max}$ $\qquad (3\text{-}27)$

$\mu_i = \mu$ $\qquad (3\text{-}28)$

$v_i = -v$ $\qquad (3\text{-}29)$

$\alpha_{CC} = 15^{\circ}(\text{max. (L/D) condition})$ $\qquad (3\text{-}30)$

CALL PREDICTION SUBROUTINE $\qquad (3\text{-}31)$

$R_{D_1} = R_{D_{TOT}}$ $\qquad (3\text{-}32)$

$X_{TG} = X_D - R_D$ $\qquad (3\text{-}33)$

Go to 10 $\qquad (3\text{-}34)$

40 NDX = 3 $\qquad (3\text{-}35)$

$$\alpha_{AA} = (\alpha_A)_{max} \tag{3-36}$$

$$\alpha_{CC} = 50^\circ \text{ (min. (L/D) condition)} \tag{3-37}$$

CALL PREDICTION SUBROUTINE $\tag{3-38}$

$$R_{D_2} = R_{D_{TOT}} \tag{3-39}$$

CALCULATE SENSITIVITY COEFFICIENTS

$$S_2 = R_{D_1} - X_{TG} \tag{3-40}$$

$$S_1 = R_{D_1} - R_{D_2} \tag{3-41}$$

$$\alpha_{C_i} = 15 (1 + 35^* S_2/S_1) \tag{3-42}$$

Go to 10 $\tag{3-43}$

50 NDX = 4 $\tag{3-44}$

$$\alpha_{AA} = (\alpha_A)_{max} \tag{3-45}$$

1F J, (51, 52, 52) $\tag{3-46}$

51 $\alpha_{CC} = \alpha_{C_i}$ $\tag{3-47}$

J = 1 $\tag{3-48}$

Go to 53 $\tag{3-49}$

52 α_{CC} α_C $\tag{3-50}$

53 CALL PREDICTION SUBROUTINE $\tag{3-51}$

$$R_{PRED} = R_{D_{TOT}} \tag{3-52}$$

Go to 10 $\tag{3-53}$

60 NDX = 5 $\tag{3-54}$

DLTX = $X_{TG} - R_{PRED}$ $\tag{3-55}$

61   1F, ABSF (DLTX - X_{TOL}) 62, 62, 63   (3-56)

62   NDX = 6   (3-57)

    Go to 10   (3-58)

63    $\alpha_{CC} = \alpha_C - DLTX * 35/S_1$ (3-59)

CALL PREDICTION SUBROUTINE   (3-60)

$R_{PRED} = R_{D_{TOT}}$ (3-61)

    Go to 61   (3-62)

3.7.3.2 Display Control Equations

70   NDX = 1   (3-63)

    SF1 = S_1 (3-64)

    SF2 = S_3 (3-65)

CALL READOUT SUBROUTINE →FLUID DISPLAYS   (3-66)
    FOR SF1 AND SF2

    Go to 10   (3-67)

3.7.3.3 Re-Entry Path Control Equations

10   1F, (v) 11, 11, 13   (3-68)

11   1F, (N - 1) 12, 12, 13   (3-69)

12    $\gamma_A = \gamma_{re}$ (3-70)

$\theta_P = (\alpha_A)_{max} - \gamma_A$ (3-71)

CALL READOUT SUBROUTINE → TO ATTITUDE CONTROL   (3-72)
    FOR (θ_P) COM.

    Go to 20   (3-73)

13    $(C_{L_C})_D = f(\alpha_C)$ (vehicle characteristics)   (3-74)

$(q)_{com}Y = (31.42 - 4.726 \times 10^{-8} V_T^2) \Big/ (C_L)_D \ A/m$ (3-75)

$C_{L_o} = (C_L)_D$ (3-76)

$(C_L)_E = f(\theta_P)$ (vehicle characteristics)   (3-77)

$$q_m = A_V/(C_L)_E \, A/m \tag{3-78}$$

$$K_1 = f(q_m) \tag{3-79}$$

$$K_2 = f(q_m) \tag{3-80}$$

$$C_D = f(\theta_P) \text{ (vehicle characteristics)} \tag{3-81}$$

$$v_{eq} = 1.64 \times 10^5 \, C_D/\mu C_L \tag{3-82}$$

$$(C_L)_{com} = C_{L_o} - [q_c - K_1 q_m + K_2(v - v_{eq})] \tag{3-83}$$

$$(\theta_P)_{com} = f(C_L)_{com} \text{ (vehicle characteristics)} \tag{3-84}$$

CALL READOUT SUBROUTINE   TO ATTITUDE CONTROL
    FOR (θ_P) COM. $\hspace{4cm}$ (3-85)

3.7.3.4 Atmospheric Range Prediction Equations (Prediction Subroutine)

$$1F_1(N - 1) \; 101, \; 101, \; 102 \tag{3-86}$$

$$101 \quad V_{N_A} = \mu_i/2.5782 \times 10^{-4} \tag{3-87}$$

$$\gamma_i = v_i/\mu_i \tag{3-88}$$

$$P_{L_A} = \frac{0.5(\gamma_i)^2 - \left[0.2365 \left(\dfrac{V_{N_A}^2 - 1}{V_{N_A}^2} \right) \left(1 - 0.2405\alpha_{AA} \right) \left(\gamma_i \right) \right]}{1640 \, (A/m \, \sin^2 \alpha_{AA} \cos \alpha_{AA})} \tag{3-89}$$

$$\Delta\mu = -44.55 \left[\gamma_i(25 + 716 \sin^3 \alpha_{AA}) \right] \tag{3-90}$$

$$q_{L_A} = P_{LA} (\mu_i + \Delta\mu)^2/2 \tag{3-91}$$

$$h_{L_A} = 1.61 \left[L_\eta(2.59 \, P_{L_A}) \right] \times 10^3 \tag{3-92}$$

$$R_{D_A} = (\mu_i + \Delta\mu/2) * t_A \tag{3-93}$$

3-29

$$t_A = 1.5 (350,000 - h_L) / v_i \qquad (3-94)$$

$$102 \quad R_{D_A} = 0 \qquad (3-95)$$

$$t_A = 0 \qquad (3-96)$$

$$103 \quad V_{N_C} = \mu_i / 2.5782 \times 10^{-4} \qquad (3-97)$$

$$X = 0.976 / (1.0 - V_{N_C}^2) \qquad (3-98)$$

$$R_{D_C} = \frac{1.13}{57.3} \left\{ \left[117.5 - 1.81 (\alpha_{CC} - 15^o) \right] \left[L_\eta(X) \right] \right\} \times 10^7 \qquad (3-99)$$

$$t_C = 4.68 R_{D_C} \times 10^{-5} \qquad (3-100)$$

$$R_{D_{TOT}} = R_{D_A} + R_{D_C} \qquad (3-101)$$

$$T_{TOT} = T_A + T_C \qquad (3-102)$$

Section 4

COMPUTATION AND LOGIC (DIGITAL INTEGRATOR)

4.1 SUMMARY

The ability of no-moving-parts fluid amplifiers to perform all the standard logic functions, while displaying superior tolerance to adverse environments, has led many people to consider their application in computational equipment. Such equipment is characterized by the need for a large number of similar "building-block" elements and frequently sets the reliability level of a system. This will be especially true in space systems where radiation, temperature extremes, long life (both operating and nonoperating), and high vibration levels must be tolerated.

This section considers the possibility of applying fluid amplifiers for logic and computation from the standpoint of implementation and performance. The reliability aspects of applying fluid devices are considered in Section 9, "Reliability," of this report.

The first characteristic of fluid logic that must be considered in examining a potential application is the operating speed. The State-of-the-Art study (Phase I) found that the present capability for switching time is about 500 microseconds with speeds of 100 microseconds appearing possible in the near future. This would limit clock rates to the range of 1,000 to 10,000 cps. While this is far slower than familiar electronic circuits, it is still adequate for a large number of space applications. Electronic computational equipment is normally designed for higher speeds to keep down the physical size of components, and because this permits the use of standard components for a broad range of applications.

The second area that must be considered in applying fluid logic is power consumption. Section 10, "Power Sources," of this report discusses power consumption and power supplies. Logic stages in the present state-of-the-art can be designed for power consumptions of 500 to 100 milliwatts per element.

Development of smaller elements and operation at lower pressure shows potential for reducing this consumption by ten to one or better. In examining power consumption, it is necessary to take account of certain unique features of the fluid elements. For example, a fluid flip-flop is a single element, unlike its electronic counterpart; several functions can be performed passively by fluid elements without additional power consumption.

Fluid logic can compete well with present day electronic logic on a size and weight basis, although molecular electronic equipment will probably be smaller than foreseeable fluid equipment. Complete fluid circuits can be molded or etched in single pieces with all the necessary interconnections, much like a printed circuit board. A major difference, however, is that the fluid elements are an integral part of the board and need not be assembled to it.

4.2 SELECTION OF DIGITAL INTEGRATOR

In seeking to identify suitable applications for this phase of the program, it soon became evident that every possible application involving logic or computation was being recommended on the basis of superior reliability. To attack this part of the applications spectrum most economically, the Phase II study considered reliability as a separate area of study (reported in Section 9) and considered computation as a second area, reported in this section. With these fundamental considerations in hand, each application problem then could be considered more realistically as to how appropriate the fluid devices may be.

In order to get a realistic appraisal of the logic and computational ability of fluid elements, it was necessary to consider a complete functional circuit; performance of a useful circuit cannot be assumed equal to performance of a single element. Because it appeared so frequently as a basic block in both control and computational equipment, the digital integrator was chosen as a vehicle for interpreting performance of an element into the capability of a useful circuit. The digital integrator is sufficiently complex to be representative of the problems that will be encountered in most applications, but can

be handled as an independent block so that useful interpretations can be obtained. Both serial and parallel implementations of the integrator were considered. Typical examples of the use of the digital integrator to generate functions are illustrated in paragraph 4.5.

4.2.1 CIRCUIT DESCRIPTION

A generalized block diagram of the integrator is shown in Figure 4-1. The integration function is performed by the device through the following numerical approximations:

$$\int y \, dx = \sum_{i=1}^{n} y \, \Delta x \qquad (4-1)$$

Several implementations were examined and were based upon the following assumptions:

1. The "fan-out", or drive capability, for a given logic element was three.

2. A resolution of 10 bits was assumed. This is equivalent to one part in 1024 and should be sufficient for many applications.

4.3 INTEGRATOR MECHANIZATION

It became apparent that three possible implementations of the integrator should be examined to cover the range of clock and iteration rates involved. These were the serial mechanization (Figure 4-2), the parallel mechanization utilizing ripple carry (Figure 4-3), and synchronous mechanization.

With the serial mechanization (Figures 4-4 through 4-7), iteration rates of 100 per second could be obtained for clock rates of 1000 pps and an iteration rate of 10,000 per second for a 100 kc clock rate. Approximately 85 fluid elements would be required to implement this serial logic building block. Most of them are employed for memory in the shift register.

A mechanization which would allow a faster iteration rate is the parallel mechanization shown in Figure 4-3. The layout of the fluid elements is shown in Figures 4-8 and 4-9. Depending upon the delays through a given logic element, the parallel implementation can give iteration rates (per integrator)
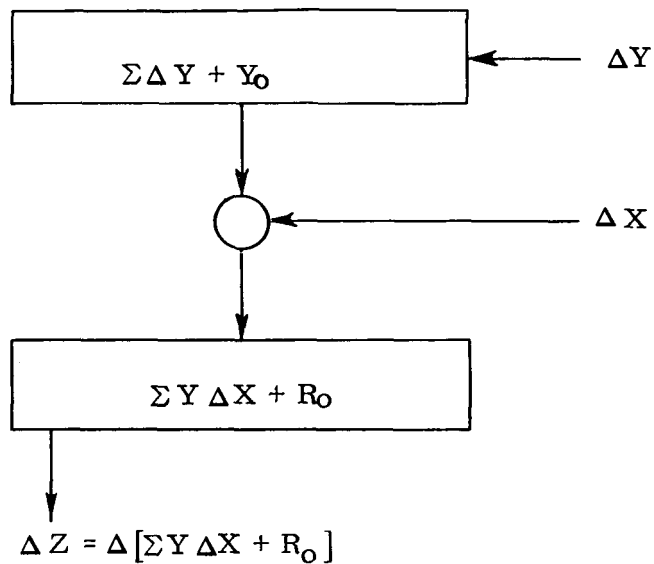
Figure 4-1. General Block Diagram of Digital Integrator.
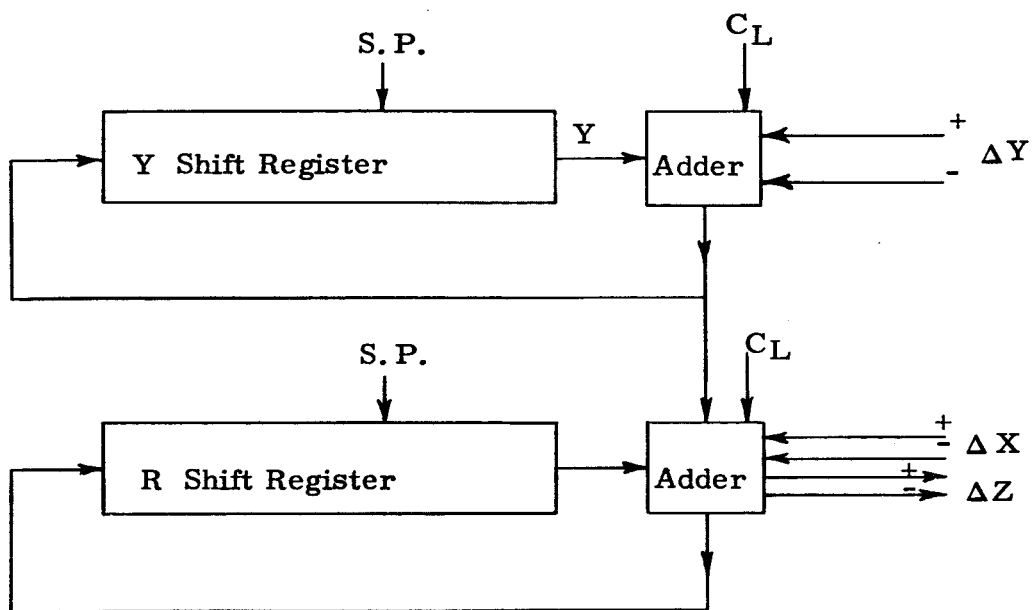
Figure 4-2. Block Diagram of Serial Digital Integrator.
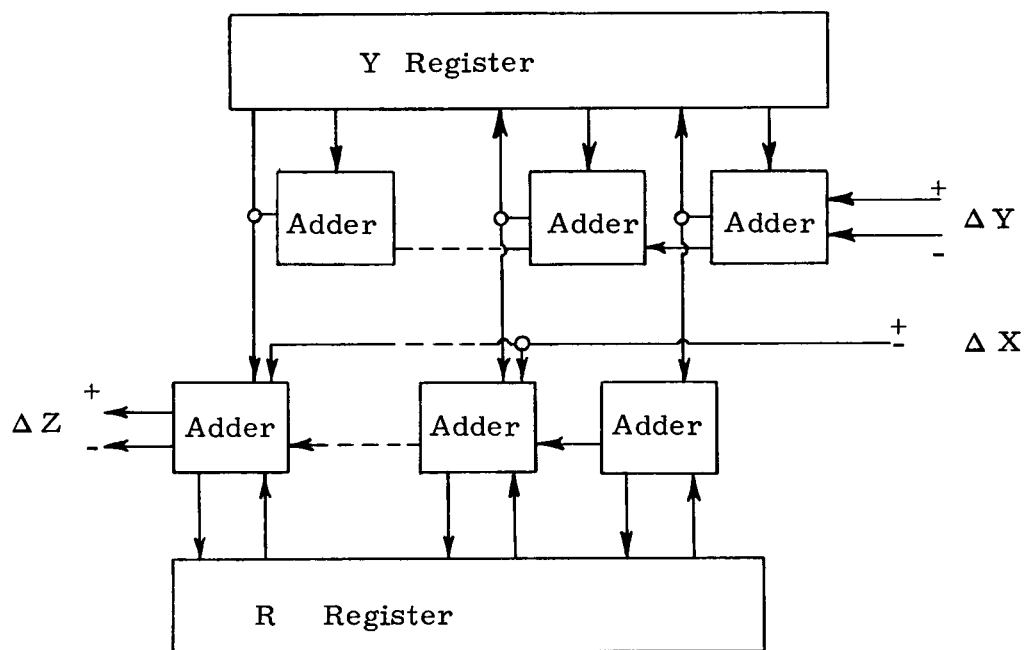
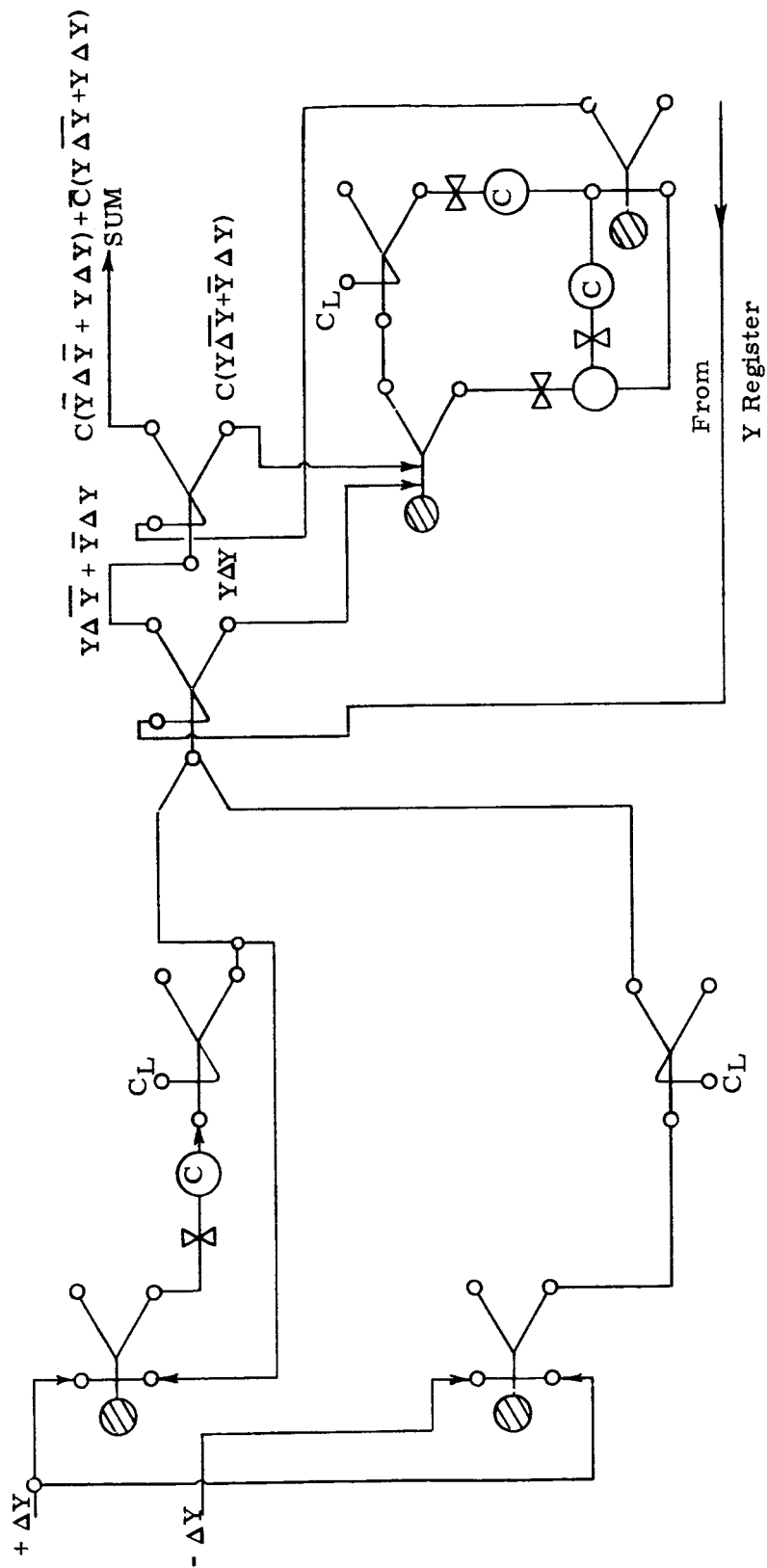Figure 4-3. Block Diagram of Parallel Digital Integrator.

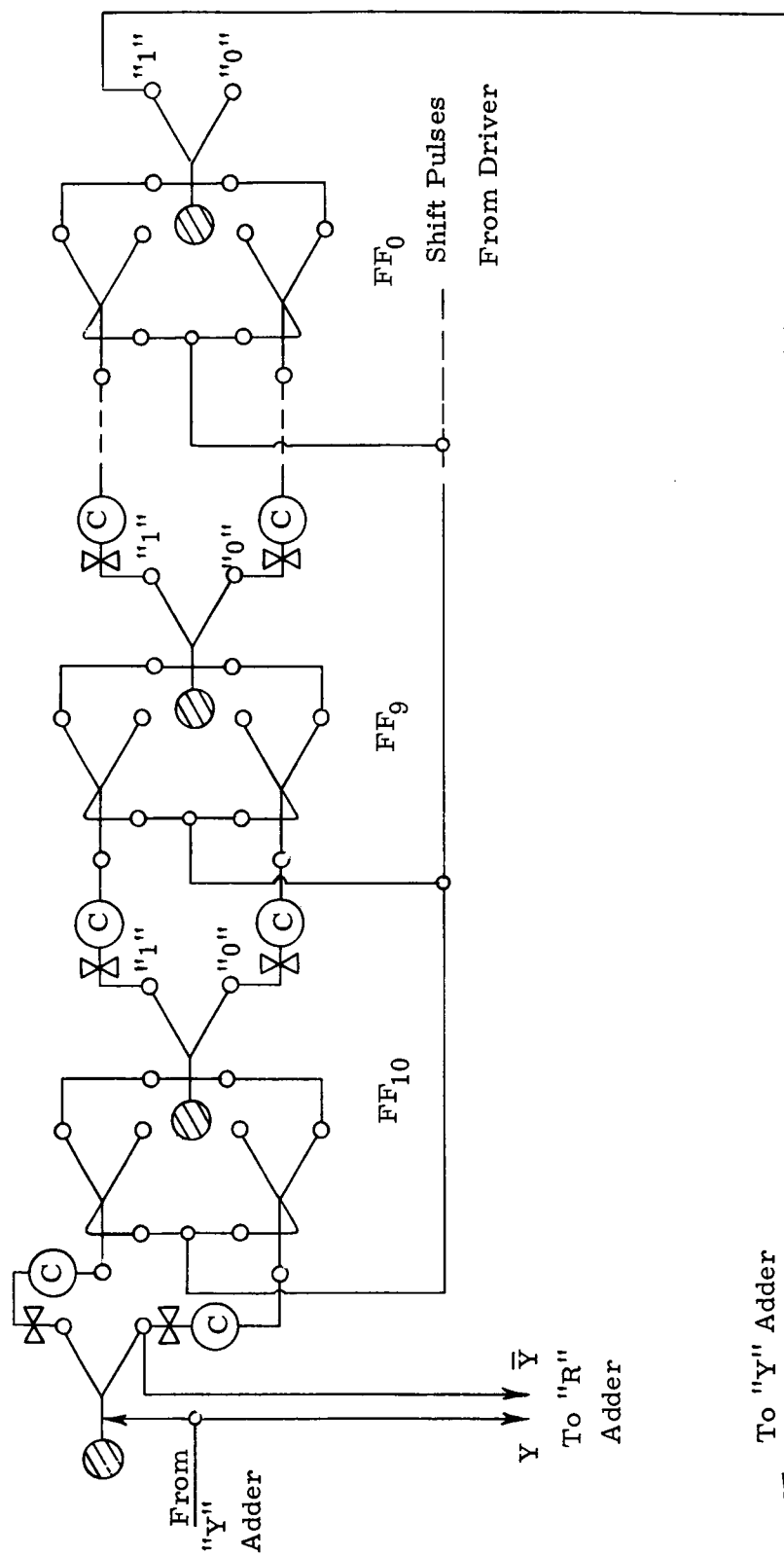Figure 4-4. Serial "Y" Adder and Control.
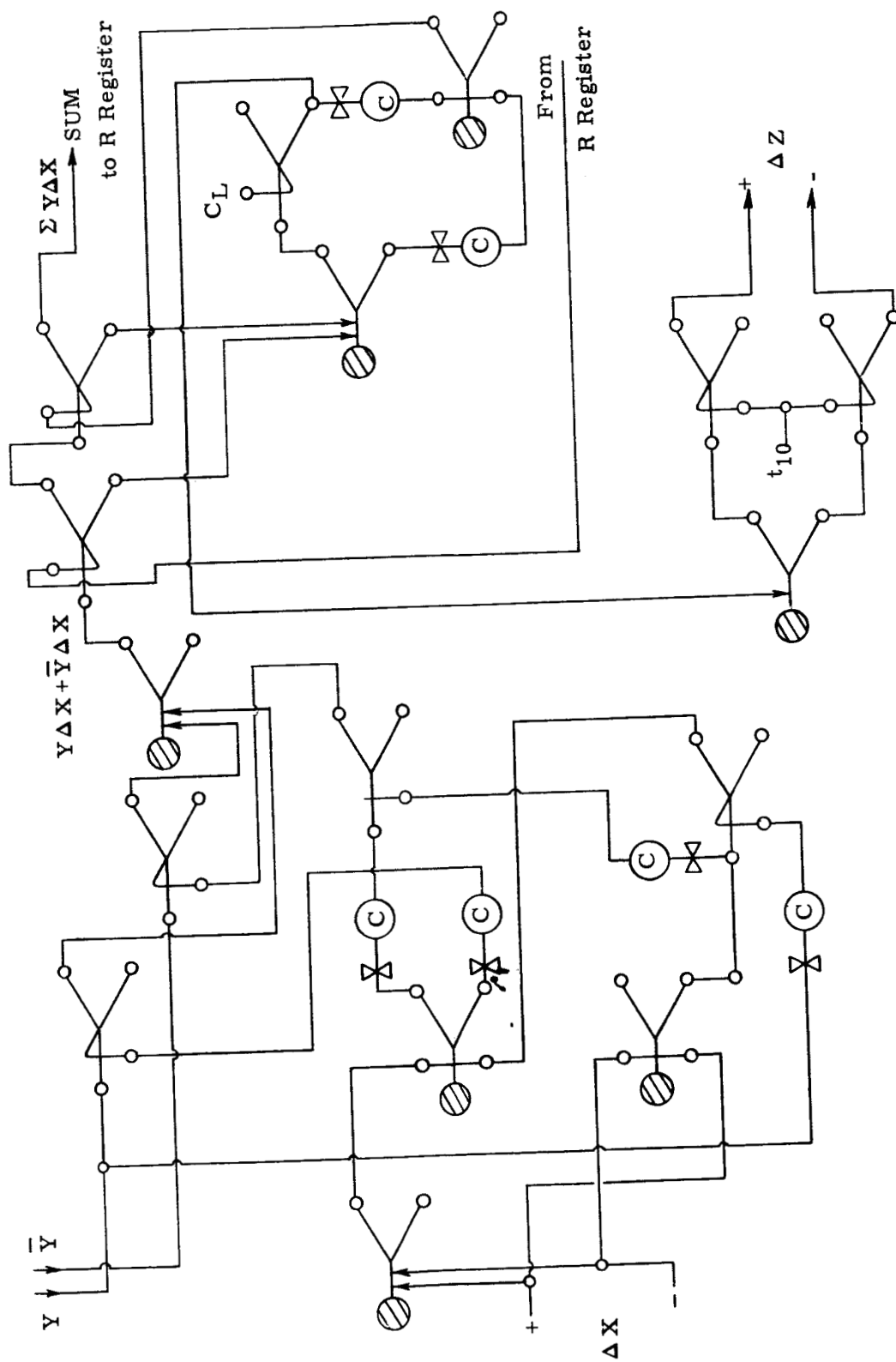
Figure 4-5. "Y" Shift Register.
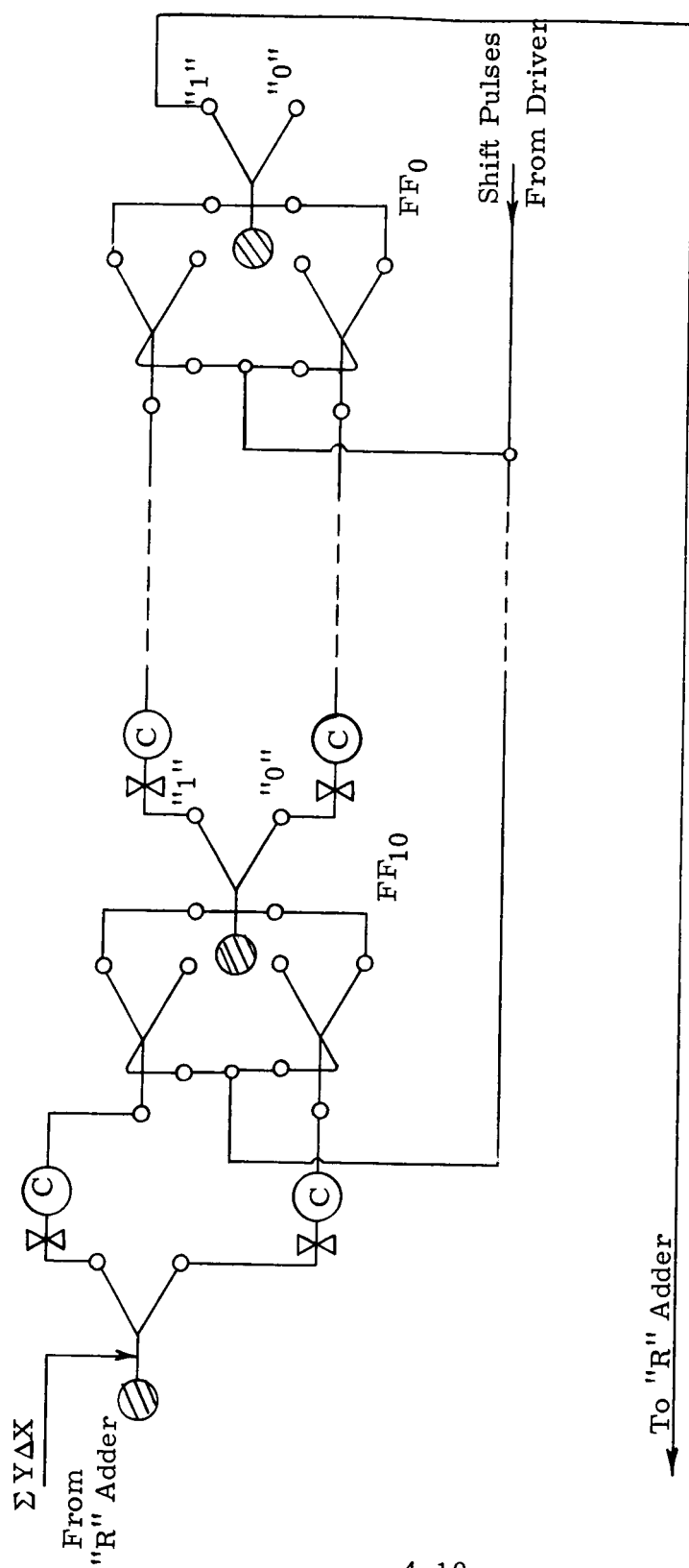
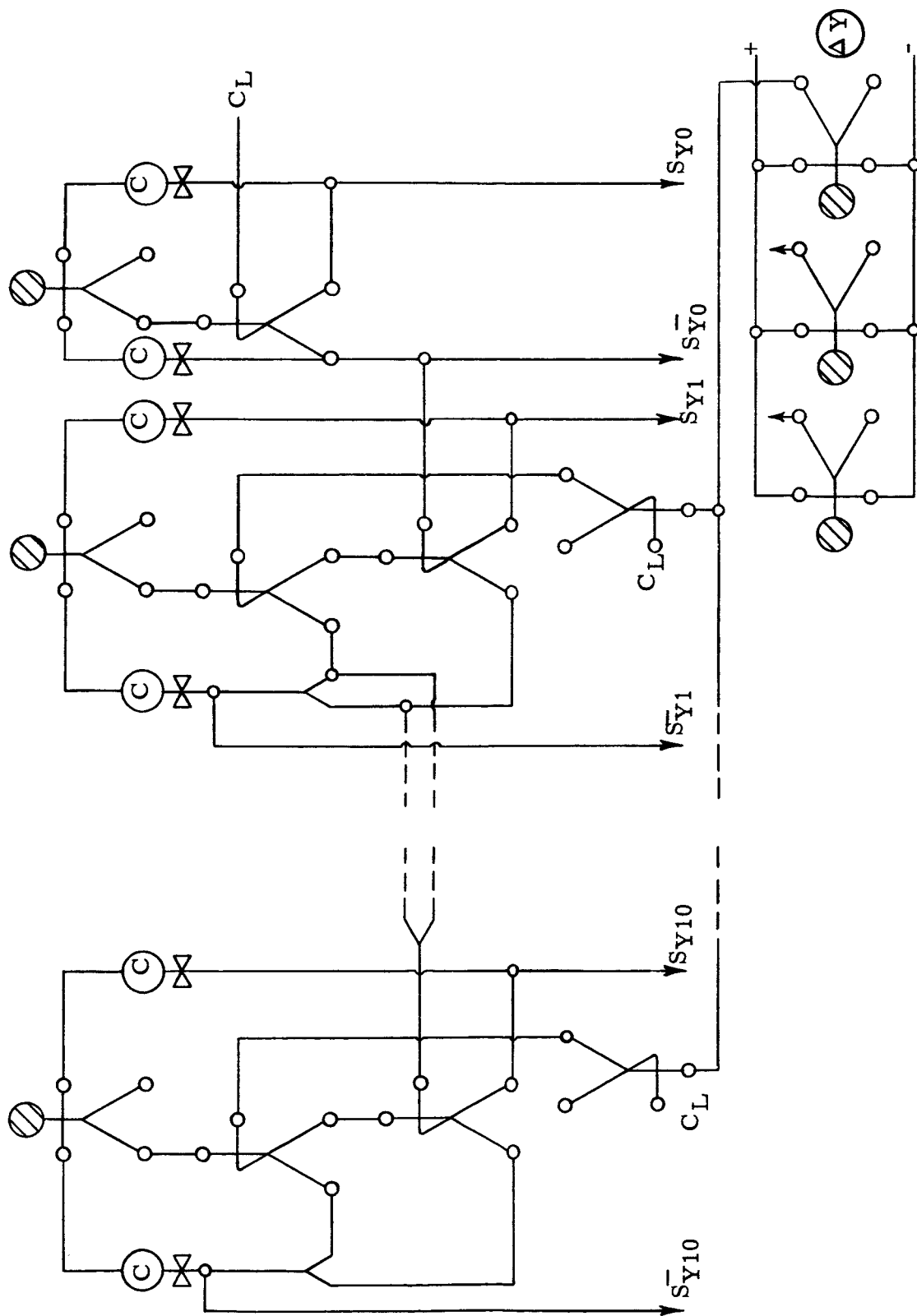Figure 4-6. "R" Adder and Control.

Figure 4-7. "R" Shift Register.

Figure 4-8. "Y" Parallel Ripple Register and Adders.

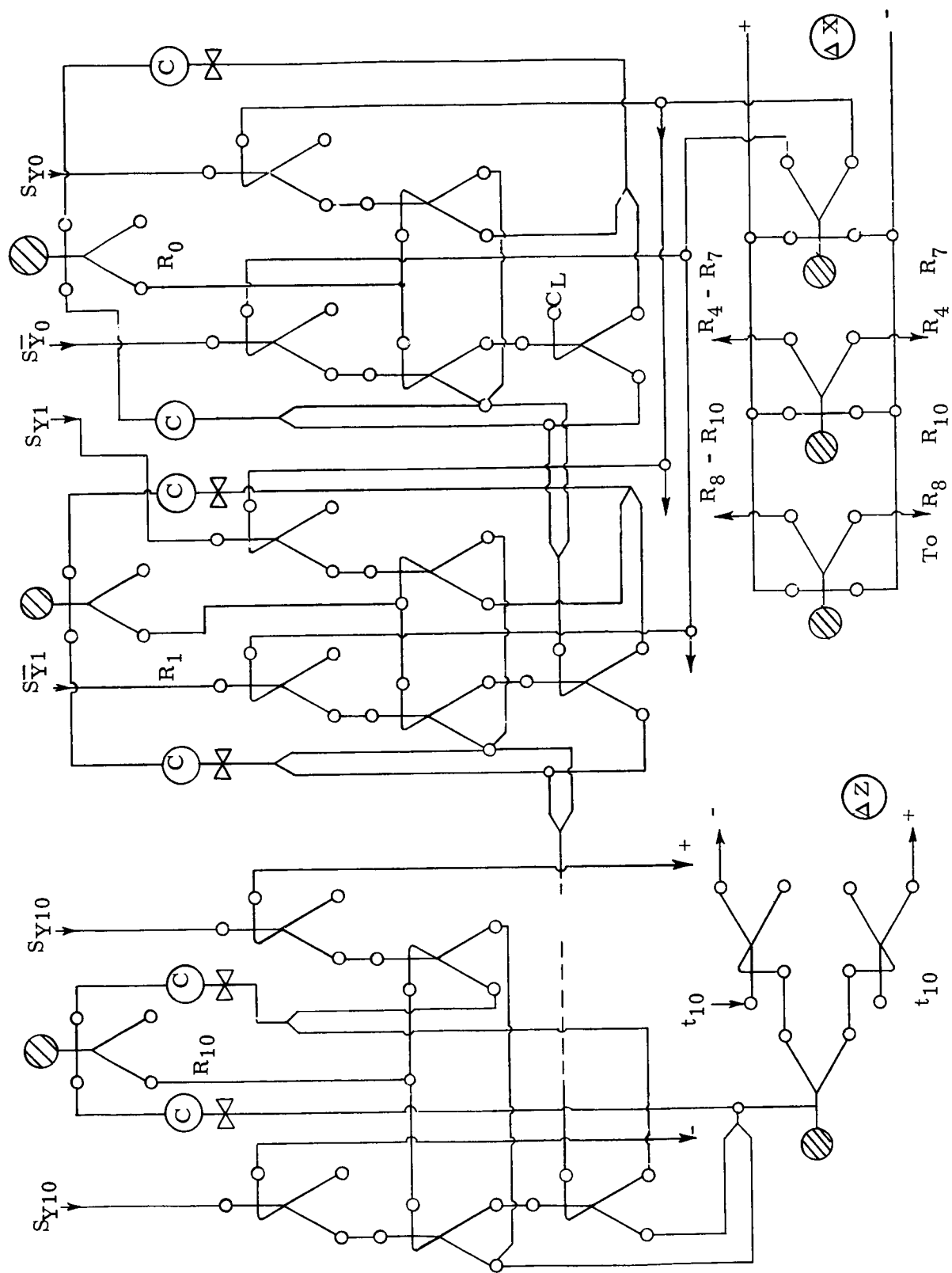Figure 4-9.   "R" Parallel Register and Adders.

approaching 1000 per second or as low as 100 per second for one kc clock rate. For a clock rate of 100 kc, iteration rates as high as 100 kc are theoretically possible. If the logic delays are large, the iteration rate of the parallel integrator could be as low as 10,000 per second for a 100 kc clock. The reason for this large iteration range is that operation of the integrator depends on the carry propagating or "rippling" through a large number of logic elements. Under certain conditions, it may be required to ripple through all 10 levels of logic.

On the average, it can probably be expected that the parallel implementation of the integrator can give about a three to one improvement in iteration speed over the serial integrator. Figure 4-10 shows the external connections required if the digital integrator is an integrated device made from one block of material with internal connections between registers and adders.

A third possible implementation is the use of synchronous logic in which each element is shifted simultaneously with clock pulses. A preliminary study of this implementation indicates that it is impractical because of the very large number of elements required. Even when ripple through two elements or a two-element delay is permitted the number of elements for the digital integrator is 4000. Therefore, synchronous implementation has not been considered further.

4.4   APPLICATIONS OF THE DIGITAL INTEGRATOR

4.4.1   SATELLITE ATTITUDE CONTROL

A sample computation used in a satellite attitude control is indicated by the following set of three simultaneous equations. The computed quantities $\Delta\Theta_x$, $\Delta\Theta_y$, and $\Delta\Theta_z$ represent the incremental angles through which the control gyros must be torqued. The implementation of the solution of one equation is shown by the integrator map shown in Figure 4-11. Excluding the generation of the sines and cosines (which can also be accomplished using integrators) the mechanization requires four integrators. Since the angular rates normally encountered in a space application of this type are low, the iteration or solution rate of the integrators could be anywhere between 1 to 10 per second. Serial
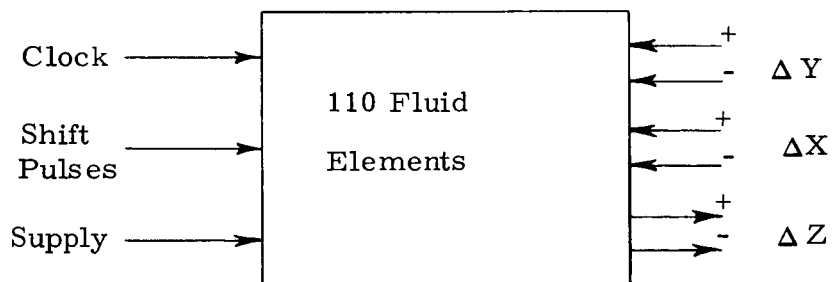
Serial Integrator

Clock →

Shift Pulses →

Supply →

85 Fluid Elements

+ ΔY
-

+ ΔX
-

+ ΔZ
-

Parallel Integrator

Clock →

Shift Pulses →

Supply →

110 Fluid Elements

+ ΔY
-

+ ΔX
-

+ ΔZ
-
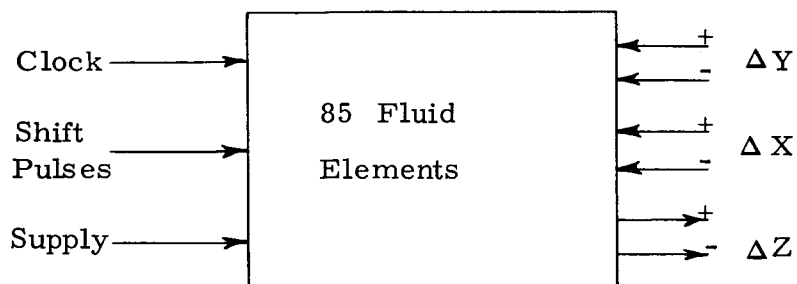
Figure 4-10.   Integrated Digital Integrators.

$$\Delta X = \frac{1}{\text{Sin } X} \quad (\text{Cos } Z \Delta Z - K \Delta \Theta_Y) \tag{2}$$

$$\Delta Y = \frac{1}{\text{Sin } Y} \quad (\text{Cos } X \Delta X - K \Delta \Theta_Z) \tag{3}$$

$$\Delta Z = \frac{1}{\text{Sin } Z} \quad (\text{Cos } Y \Delta Y - K \Delta \Theta_X) \tag{4}$$
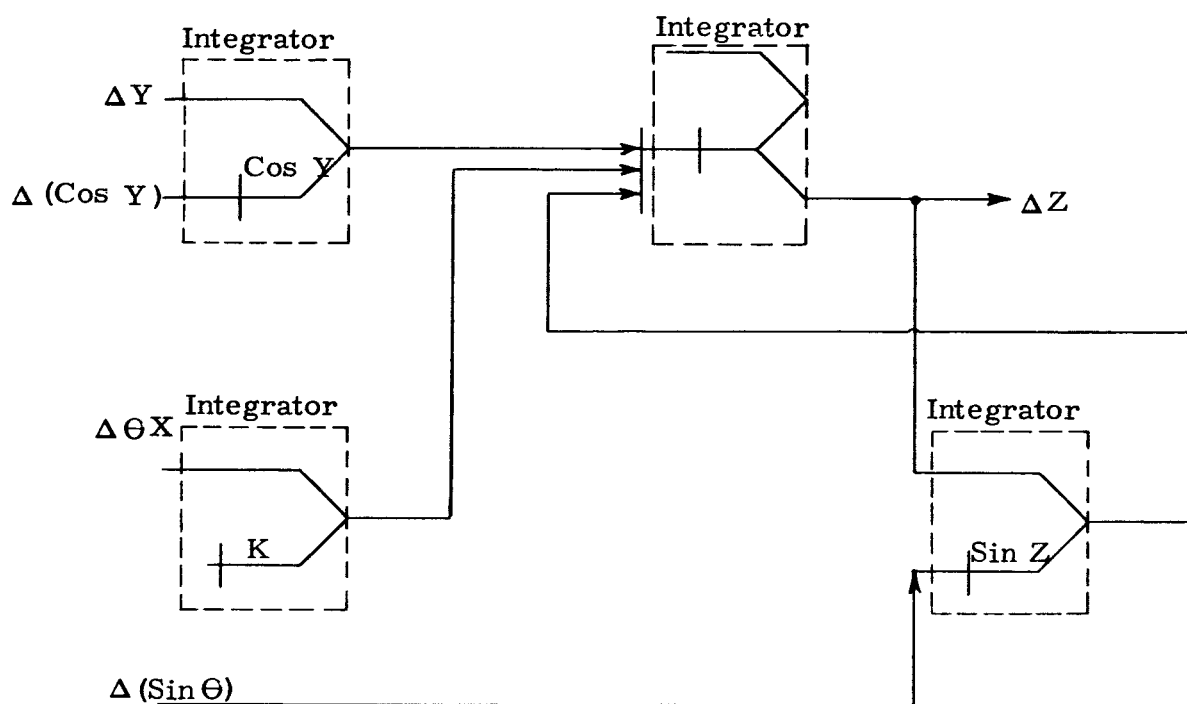
Figure 4-11.   Integrator Map for Solution of:

$$\Delta Z = \frac{1}{\text{Sin } Z} \quad (\text{Cos } Y \Delta Y - K \Delta \Theta_X)$$

implementation of the integrators, interconnected as shown, would require clock rates from 100 to 1000 cps for a resolution of one part in a thousand. These clock rates are within the realm of fluid logic operation.

4.4.2 NAVIGATION

Another possible application is the area of inertial navigation where integrators can be used to integrate acceleration signals into velocity and position information. A portion of a typical gimballed inertial navigation system mechanization is shown in Figure 4-12. Acceleration correction signals due to coriolis are shown as inputs. These corrections C_N, C_E, and C_V are also generated by a group of four integrators. In addition, the generation of trigonometric sines and cosines needed in the computation of the coriolis corrections are implemented by a set of coupled integrators.

The pulse rates normally encountered for terrestrial navigation or ballistic missile guidance may be quite high -- in the order of 1,000 to 2,000 pulses per second for ΔV_N, ΔV_E, and ΔV_V. However, in space applications, where accelerations are small, the rate may be in the order of 10 to 100 pps. If an input pulse rate of 1000 per second is required, then the iteration rate of each of the input integrators may be in the order of 1,000 per second. The clock rate of an integrator (assuming 15-bit resolution) would have to be 15,000 pps. For the 10 pps input rate, the integrator clock would be 150 pps.

The other integrator rates would be somewhat lower because the change or pulse rates in the integrated outputs of the first integrators would be lower (probably in the order of 1 to 10 pps for the high speed), 1000 iterations per second and 0.1 to 1 pps for the 160 iterations per second. The exact numbers would depend upon the scaling employed. This type of navigation mechanization was employed on the Inertial Survey System (U.S. Army contract No. DA-44-009-ENG-4413).

4.4.3 VEHICLE CONTROL

Another possible application is the use of integrators in vehicle control. A typical portion of a control implementation of a rate generator which could be part of a digital position servoloop is shown in Figure 4-13. Mechanization of the filter device is shown by the integrator map below the block diagram.
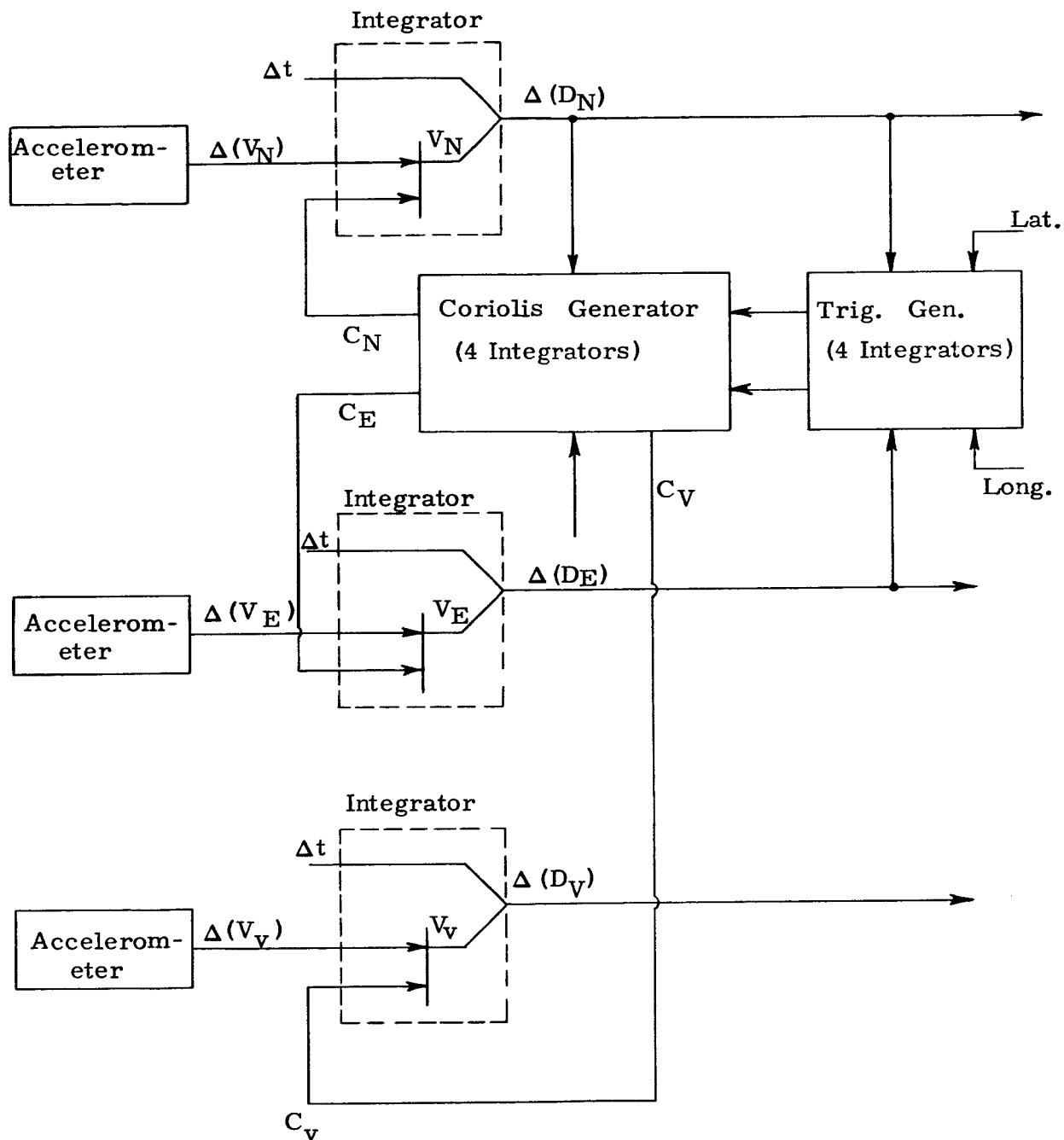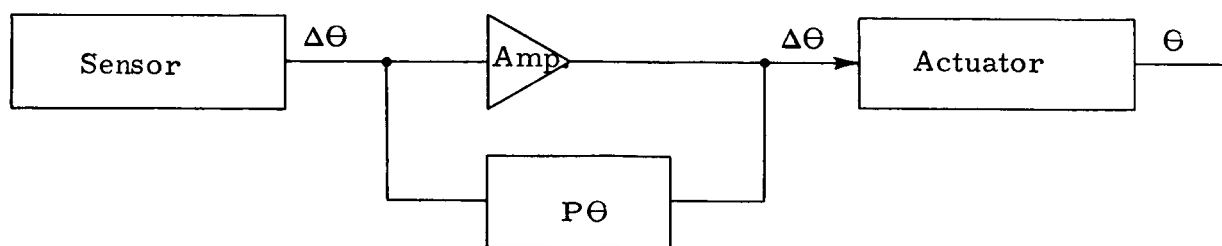
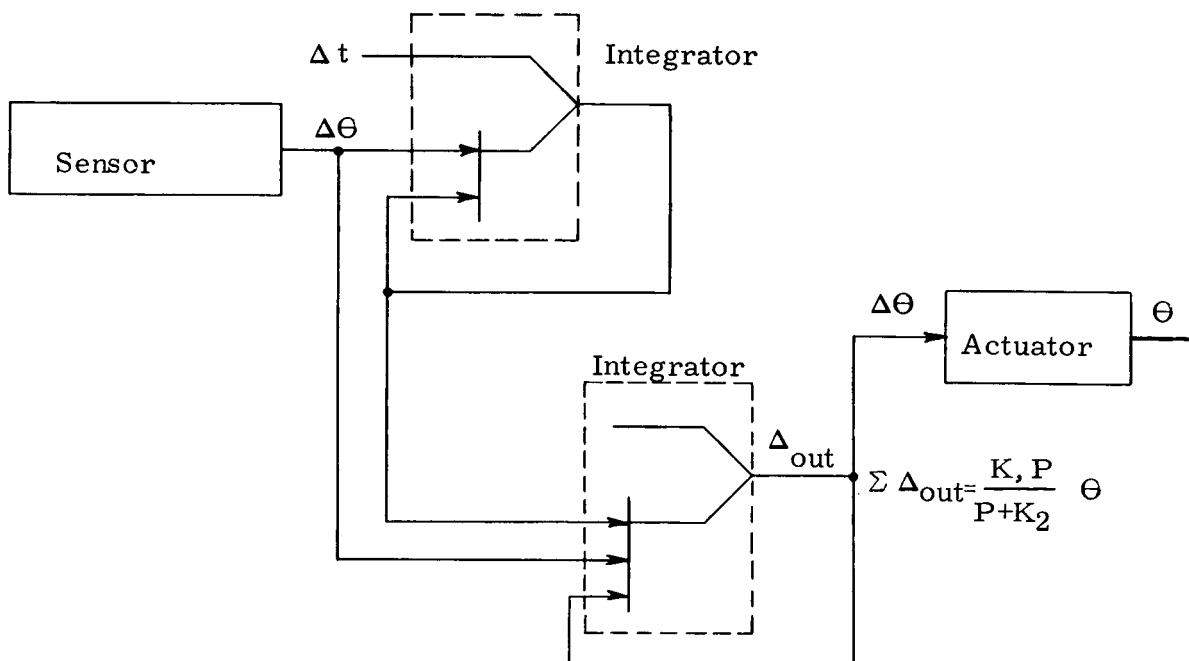Figure 4-12. Use of Integrators in Inertial Navigation.

Position Servo

Figure 4-13.   Digital Position Servo.

A mechanization of this form was implemented on vehicle control contract AF 33(616)-8351 for the U.S. Air Force.

Pulse rates involved here (especially in space application) could be very low -- in the order of 1 to 10 per second for $\Delta\Theta$ inputs. Therefore, the iteration rates could be very low (1 to 10 per pps) and the required clock would be approximately 10 to 100 pps .

4.5 SUMMARY

State-of-the-art fluid elements can be used to implement a serial digital integrator of 10 bits (one part in 1024) with iteration rates of 100 per second (1000 cps clock). Larger numbers of bits are possible but will result in proportionately slower iteration rates. As higher speed elements are developed, the rates can be raised proportionately.

Iteration rates approaching 1000 per second (1000 cps clock) are possible using parallel implementation but about 30 percent more elements are needed. Speed is limited by delays in the elements and can be improved as new stages are developed.

There do not appear to be any limitations in the use of fluid elements for logic or computation per se. All the functions needed for space applications appear feasible. Each application must be examined separately to determine whether speed and power consumption are compatible, and if a real reliability gain is achieved. Comparison with electronic counterparts cannot be made on a one-to-one count basis.

Section 5

LIQUID METAL CONTROL SYSTEMS

5.1 SUMMARY

Future National Aeronautics and Space Administration space vehicles may require the use of high performance electrical power systems, such as the Systems for Nuclear Auxiliary Power (SNAP) now under consideration. SNAP systems using a Rankine cycle with a nuclear reactor and liquid metal thermal loops will require unique control systems because of the high nuclear radiation, high temperatures, and the characteristics of the liquid metals. Fluid amplifiers appear to offer the ideal solution because of their high temperature and radiation tolerance. Further, they can be made compatible with the liquid metals by the proper choice of fabricating materials.

In order to investigate the suitability of applying fluid amplifiers, reactor powered liquid metal thermal systems, such as the SNAP 50 and advanced systems now under consideration, were used as the basis for the study to obtain typical operating conditions and specifications. The initial review of such a system indicated the following possible areas or loops for application of fluid amplifiers:

1. Modulation of liquid metal flow to regulate turbine speed
2. Control of flow in radiators to limit lower temperature to prevent freezing
3. Control of reactor temperature

Initial investigation of these application areas showed Items 1 and 2 to be attractive. It was concluded that there was no particular advantage in applying fluid amplifiers to Item 3, because electrical signals (nuclear flux override and load) must be fed into the temperature control and existing electrical circuitry should be capable of performing the function. Output from the control is a signal to command a position of the control rods. Fluid amplifiers can be used in the control rod servo as described in Section 2, "Gas Servos for Engine Actuation," of this report.

5.2   TURBINE SPEED CONTROL

A typical liquid metal Rankine system is illustrated in Figure 5-1.   A nuclear reactor supplies the energy to boil the liquid metal at the system supply pressure level.   The vapor then flows through the turbine and through the condenser.   The condensate is raised back to the supply pressure level with the condensate pump.   The boiler is capable of flashing all available flow to vapor so that vapor flow to the turbine is controlled directly by controlling liquid flow.

The application of fluid amplifiers in this system is in the diverter valve area, which provides a slow response means of regulating turbine speed to produce a constant frequency electrical output.   High response control is obtained with the parasitic electrical heat dump.   The concept is to use a proportional diverter valve at the output of the pump to control the amount of flow into the boiler.   One output port from the diverter valve would be manifolded to the boiler, and the other would manifold the excess flow back to the pump inlet.   In order to have wide flow range capabilities, the pump would provide greater flow than required to the boiler at all times so that excess flow is returned continually to the pump inlet.   Although some losses occur with this arrangement, the power loss is not serious because the liquid pumping power is relatively small.   The diverter valve is controlled from a frequency error signal; the difference between the generator frequency and a reference signal.   Since this signal is electrical, an electrical/liquid-metal transducer is required.

In operation, if load is increased causing a momentary decrease in turbine speed, a frequency error signal is produced indicating the speed decrease.   This error signal will cause the diverter valve to increase the flow to the boiler.   Hence boiler pressure will increase causing the turbine speed to increase to the desired value.   This method of flow modulation eliminates sliding and moving parts.   Location of the control is in the coolest segment of the loop hence minimizing corrosion problems.   Use of suitable materials for fluid amplifiers should result in essentially no radiation

1000 KWE Net Output

Normal No-Load to Full-Load in 15 minutes
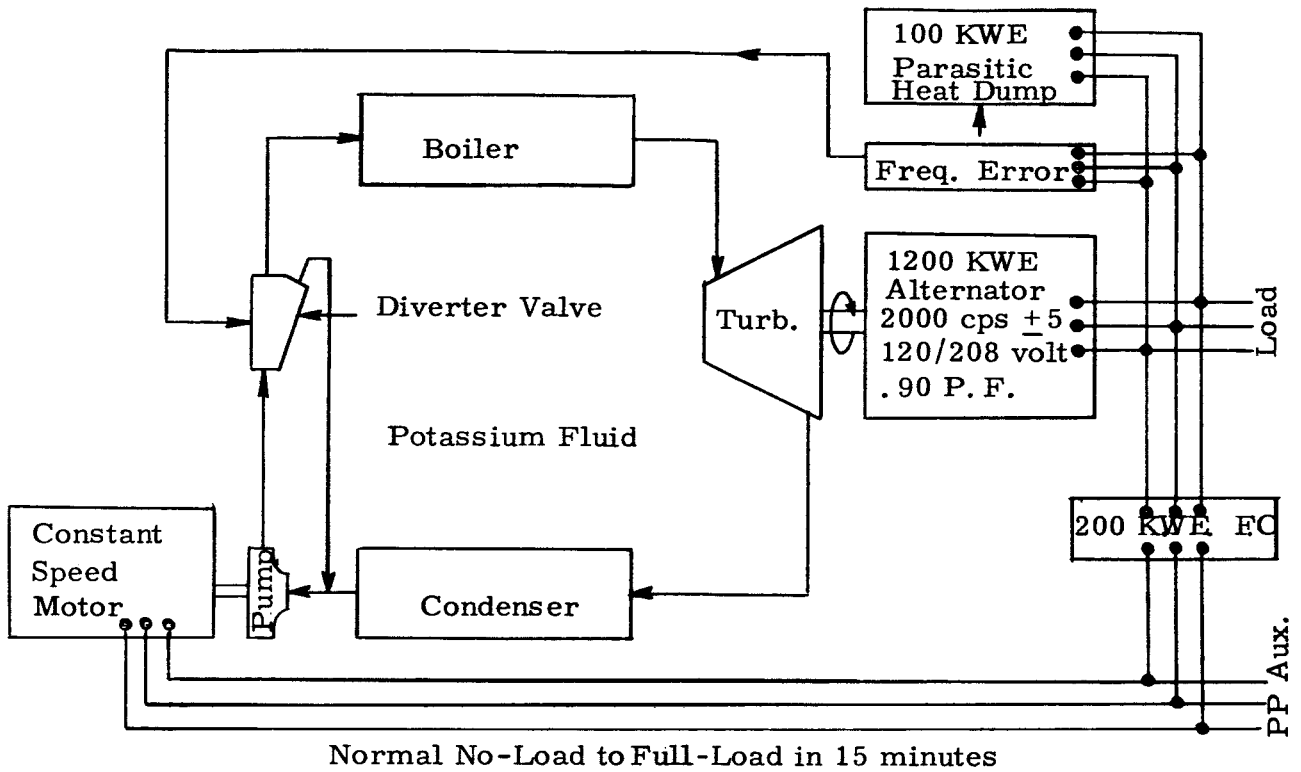
	Full Load	No Load
Condenser Exit		
Temperature	1140°F	740°F
Pressure	5 psia	2 psia
Flow rate	7.5 #/sec	2 #/sec
Boiler Inlet		
Temperature	1140°F	740°F
Pressure	125 psia	102 psia
Pump Pressure Rise	120 psi	100 psi
Alternator Power	1200 KWE	200 KWE

Figure 5-1.   Turbine Speed Control.

or corrosion problems. Some of the key operating conditions for the control are listed in Figure 5-1.

The circuitry and transducer concept envisioned for the control is shown in more detail in Figure 5-2. The arrangement would use a pump outlet pressure of 165 psia. The fluid amplifier diverter valve is sized to have about a 64 psi pressure drop across the power nozzle. Typically 35 percent of this pressure drop can be recovered in the receivers so that the maximum output pressure can be 125 psia, the pressure required at maximum load (Figure 5-1). With this recovery value, diverter valves can proportion the flow from 0 to 100 percent. With all flow diverted to the bypass, the boiler inlet pressure can be reduced to the local ambient or the minimum requirement of 102 psia. A two-stage pump can be used with the diverter flow injected into the pump between stages to prevent loss of the remaining pump energy in the diverter flow. Because of the power loss in the diverter valve, 33 percent more pump power is required. This increase is not significant since the liquid pump power is small compared to the total output of the system.

The fluid diverter is controlled in response to the frequency error signal by means of electromagnetic valves and two amplifiers. Two stages of fluid amplifiers are used to minimize the power dissipation in the electro-magnetic valves since the latter are very inefficient. The driver for the electromagnetic valves reduces current in one valve and increases current in the other on command from the frequency error. This change in current causes one valve to have a greater flow restriction and the flow restriction in the other valve to reduce. Hence, a pressure difference is generated at the control ports of amplier No. 1 which results in a fluid signal to drive the diverter valve. This transducer arrangement can be hermetically sealed, a requirement for liquid metal systems. Although only two stages of amplifica-tion are shown, trade-off studies may show more to be advantageous. Power gain of one stage is of the order of 200 which, in the system shown, results in the transducer being operated at a level of 4×10^{-4} watts, the power level of the control ports of the diverter valve.
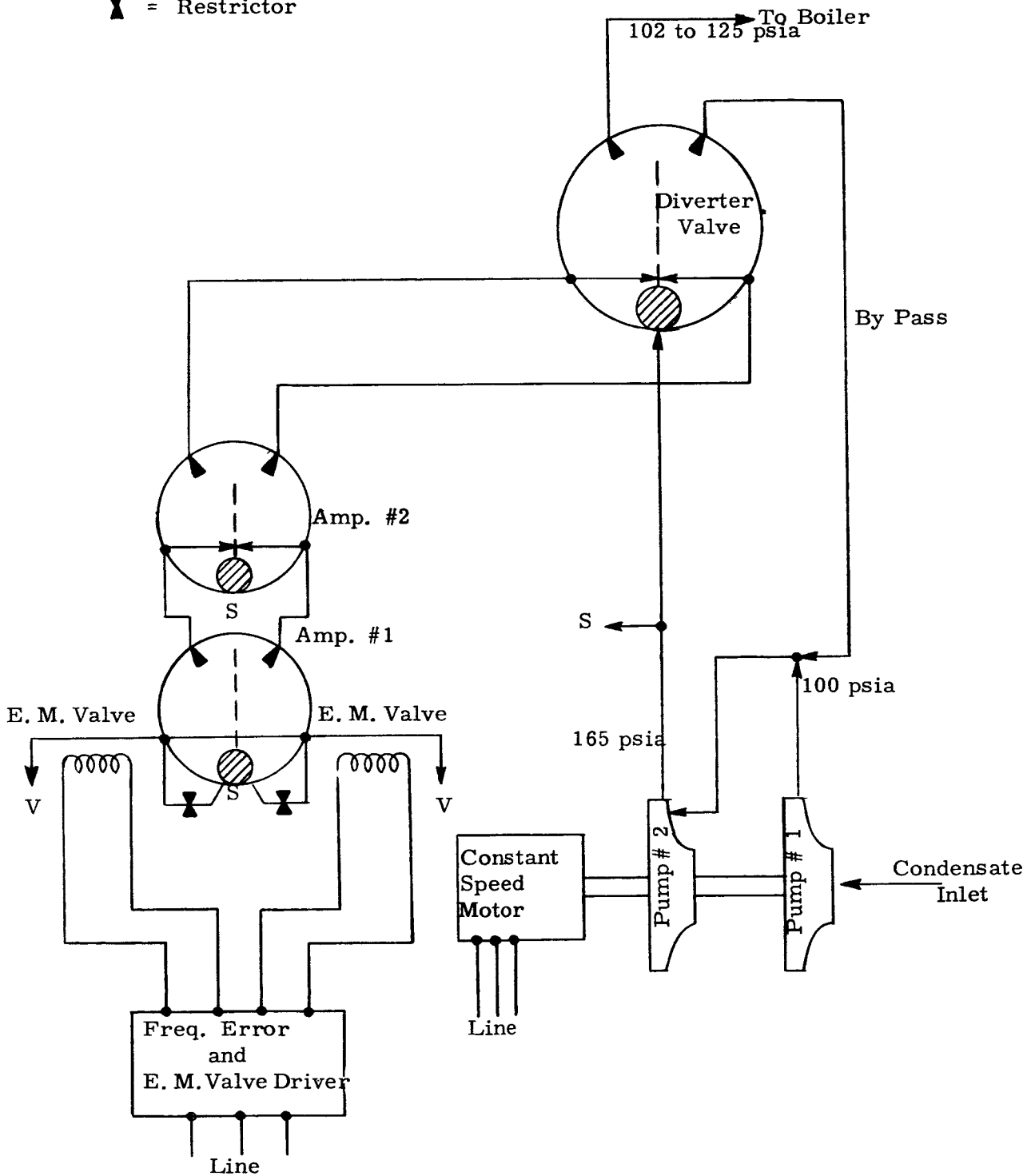
S = Fluid Amplifier Supply
V = Vent or Sump
⧓ = Restrictor

To Boiler
102 to 125 psia

Diverter Valve

By Pass

Amp. #2

S

Amp. #1

E. M. Valve   E. M. Valve

V   V

S

165 psia

100 psia

Constant Speed Motor

Pump # 2

Pump # 1

Condensate Inlet

Line

Freq. Error and E. M. Valve Driver

Line

Figure 5-2.   Fluid Amplifier Circuit for Turbine Speed Control.

5-5

5.3   COOLANT TEMPERATURE LIMIT

Nuclear-liquid metal power plants presently under consideration may use several auxiliary liquid metal loops for cooling transformers, motors, and other equipment. These loops reject heat to space by means of radiators. A control would be used on each radiator to limit and regulate the temperature of the liquid metal leaving the radiator to prevent radiator freezing.

A block diagram of a typical coolant loop is shown in Figure 5-3. The concept of the fluid amplifier control is the use of a diverter valve on the outlet of the circulating pump to vary the flow through the radiator. The temperature of the liquid metal leaving the radiator is sensed and compared to a reference to generate a temperature error signal. If the outlet temperature drops, approaching the liquid freezing temperature, the temperature error causes the diverter to bypass less flow around the circulating pump and to provide greater flow through the radiator, hence raising the exit temperature. Conversely, if the outlet temperature rises above the set value, the error signal will cause more flow to be diverted around the pump reducing flow in the radiator thereby lowering the radiator exit temperature. The circuitry for the diverter valve and pump (Figure 5-4) for this application is very similar to that described above for the turbine speed control. Use of a two-stage pump will minimize the power loss.

The frequency-temperature sensitivity of a fluid amplifier oscillator was investigated as a possible temperature sensor. This concept appears impractical because the acoustic velocity (hence frequency) changes very little in liquid metals with significant temperature changes. Another form of a temperature sensor, such as a bimetallic modulated fluid bridge, is required. The output from this sensor would be amplified to the appropriate power level to drive the diverter valve.
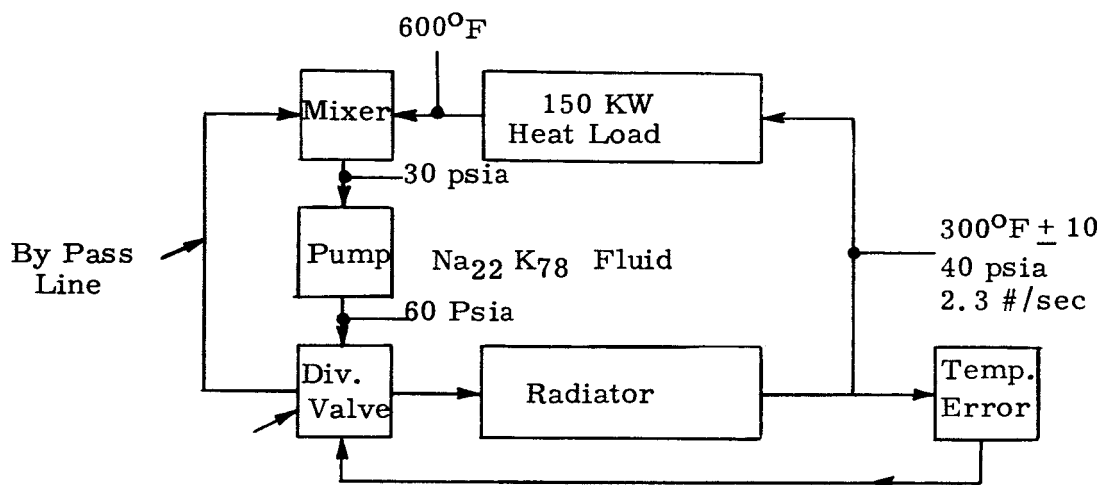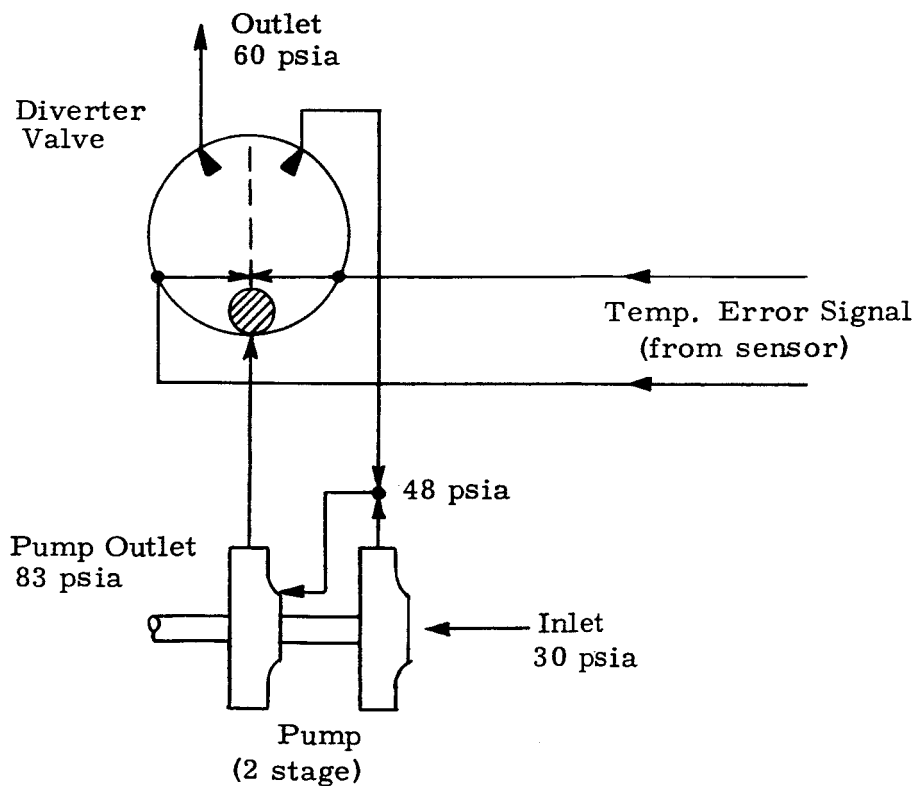
Figure 5-3. Block Diagram of Auxiliary Coolant Loop.

Figure 5-4. Schematic Diagram of Diverter Valve and Pump.

Section 6

TACTUAL PERCEPTION

6.1 SUMMARY

An astronaut is exposed to a high g evironment immediately following blast-off and for a limited time during the re-entry phase of the mission. During these periods a marked reduction in his sensorial capabilities occurs. As the g loading is increased, for example, visual perception is apparently reduced and eventually completely lost. Tactual perception, however, is not expected to be significantly affected under these conditions. In addition, it is probable that, under high g loading, the astronaut can retain his ability to make intelligent decisions.

Because of this apparent high tolerance to g loading, tactual perception is presently under investigation to determine optimum arrangements and means of usage.

6.2 TACTUAL PERCEPTION CONCEPTS

Stanford Research Institute presently is engaged in a study of tactual perception. Among the areas being investigated are the means of applying force patterns on the skin, response to various stimuli, permissible position and length of patterns, and ambiguity and learning problems. One of the more promising methods of creating force patterns is the use of an array of small air jets directed on the skin. A specific force pattern is created by turning on the proper jets in the array. Each bit of information is represented by a specific recognizable pattern. Typical patterns under investigation at Stanford are illustrated in Figure 6 -1 (Ref. 6-1). It has been learned that the skin becomes insensitive to the force if it is a steady value; a cyclic pressure variation in the jet provides maximum skin sensitivity. Typical skin areas for application of the force patterns are the back of the hand, the fingers, and

Ref. 6-1 Bliss, J.C. et al, Instrumentation for and Experiments on Tactual Perception, quarterly Report No. 1, Stanford Research Institute, December, 1963. Prepared under contracts NAS 2-1679 and AF33(615)-1099.
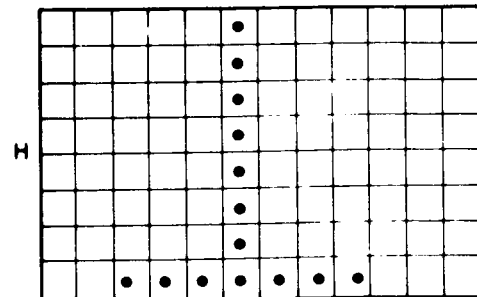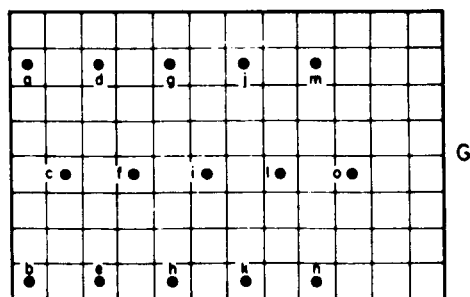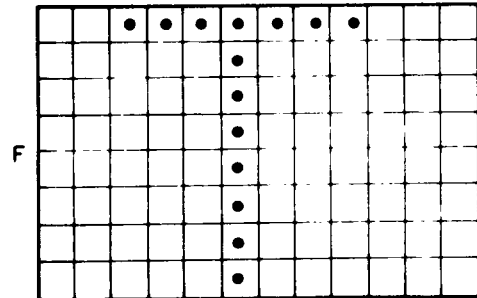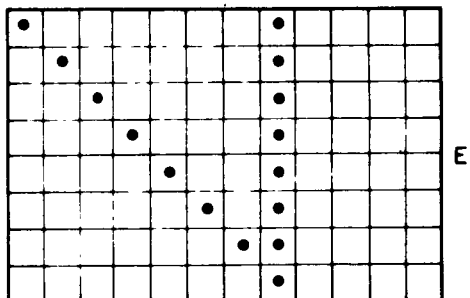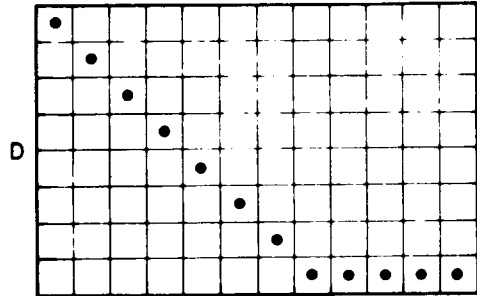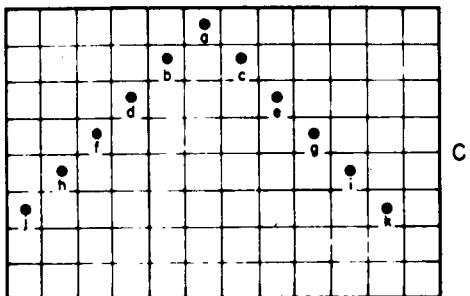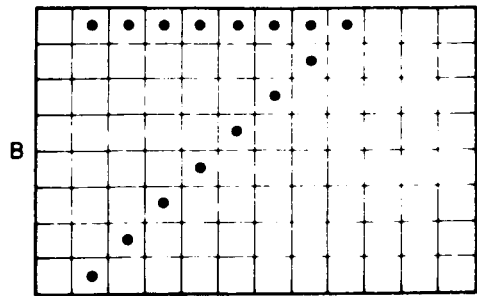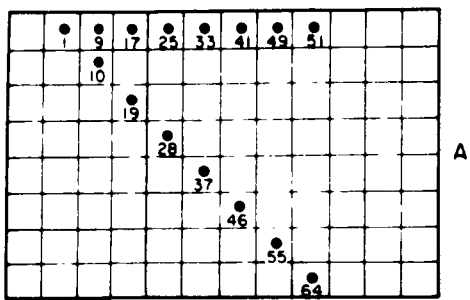
Figure 6-1. Stimuli Patterns.

the forehead. Other activity in the tactual perception field is described in References 6-2 and 6-3.

Although the experiments and work reported to date are extremely preliminary, consideration of how tactual perception would be applied in a control system leads to the conclusion that the application of fluid amplifiers is advantageous, especially if air jets are used to create the force patterns.

6.3 TACTUAL PERCEPTION CONTROL LOOP

In a typical system the astronaut performs as part of the control loop. The objective being to: 1) convey information or instructions to the astronaut by tactual means during the time intervals when other sensory methods are adversely affected; 2) retain the astronaut's judgment as part of the loop (he has a choice -- respond according to the instruction or reject); and 3) provide suitable control and storage capabilities which are compatible with the human segment of the loop, yet obtain high performance. Fluid amplifiers are attractive in this application because the required logic and information storage can be performed with fluids; and transducer problems can be minimized because the same working fluid can be used for the fluid amplifiers and the air jets in the array.

A typical tactual perception control envisioned is illustrated in block diagram form in Figure 6-2. As noted above, the astronaut forms part of the control loop. A cluster of switches, the functional control switches, will be located near his hand. He will be able to change the position of any switch he chooses during the high g portion of the mission. Normally, these switches would be operated by the astronaut after he observed the instruments and evaluated other information available within the spacecraft. When he is unable to observe the instruments because of high g's, the instructions to the fluid system would be originated by an external system. The external system would evaluate the levels of the parameters normally monitored by the astronaut's

Ref. 6-2   Hirsch, J. et al, Experiments in Tactile Communication, Technion, Haifa, Israel.

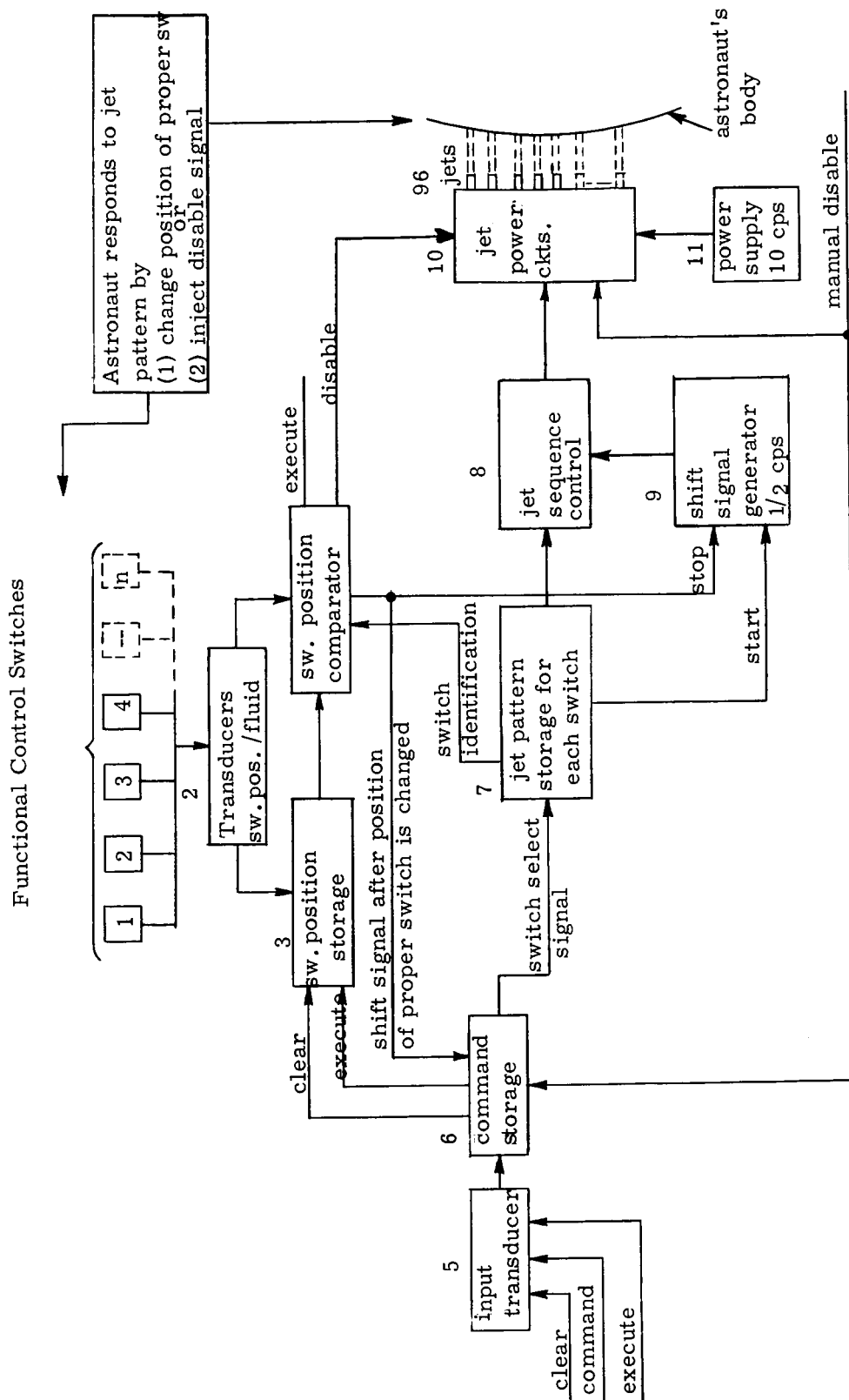Ref. 6-3   Hirsch, J. and KadushinI. , Experiments in Tactile Control of Flying Vehicles, Technion, Haifa, Israel.

Functional Control Switches

Astronaut responds to jet pattern by
(1) change position of proper sw
or
(2) inject disable signal

Figure 6-2. Fluid Logic Control System for a Tactile Sensing Application.

6-4

instruments in the spacecraft and recommend appropriate actions. The astronaut would still be free to make the final decisions however.

Operation of a tactual control system can be traced by referring to Figure 6-2, assuming there is an external system to evaluate the parameters associated with the functional control switches. A command, based on this evaluation, is fed to the input transducer (Item 5). Assume for the purpose of explanation that the astronaut will be instructed to change the position of functional control switches, 2, 4 and 1 (in that order). This information initially would be held in the command storage block (Item 6). Upon application of the "Execute" signal, the switch position storage unit (Item 3) would store the existing position of all the functional control switches. The switch position comparator (Item 4) would continuously compare the position of all the control switches with the stored positions. Next, a "Switch Select" signal is fed into the pattern storage unit (Item 7). This unit selects a jet pattern which corresponds to a specific control switch, in this case, switch No. 2. A "Start" pulse is then fed to the shift signal generator (Item 9). A 0.5 cps trigger signal is fed to the jet control circuitry. Each pulse triggers one power jet. This process continues until all of the power jets needed for the pattern corresponding to switch No. 2 are projecting an air stream upon the body of the astronaut. The air for the power jets is supplied by an oscillatory pressure power source (Item 11).

The astronaut will recognize the correspondence between the jet pattern and switch No. 2. He now has two choices. First, he can change the position of switch No. 2. If he does, the switch comparator will generate a "Shift" signal which shifts the command storage unit to switch No. 4. The astronaut's second choice is not to change the position of switch No. 2. In order to remove the jet streams from his body, he would energize the manual disable switch. This would also clear the command storage, thereby making it available for the next command from the external system.

A brief discussion of each of these functional blocks is as follows:

1. <u>Functional control switches</u> - These are assumed to be controls for systems which may require an adjustment during the high g phase of the mission.

2. <u>Transducers</u> - These are electric/fluid converters and provide the coupling between each control switch and the fluid circuitry.

3. <u>Switch position storage</u> - This is a memory circuit which will store the position of each functional control switch when the "Execute" pulse is applied.

4. <u>Switch position comparator</u> - Upon application of the "Execute" pulse, this circuit will continuously monitor the position of each functional control switch and compare these positions with those in the storage block. A shift or clock pulse is generated after the astronaut changes the position of the proper control switch.

5. <u>Input transducer</u> - These converters provide the coupling between the external system and the fluid circuitry.

6. <u>Command storage</u> - The astronaut may be instructed to change the position of more than one control switch in a definite sequence. This type of information is retained in the command storage block and is shifted to the jet control circuitry when a clock signal is generated by the switch position comparator.

7. <u>Jet pattern storage</u> - The jet patterns are stored corresponding to each of the functional control switches. The select signal from the command storage will trigger the storage block for the correct jet pattern.

8. <u>Jet sequence control circuit</u> - The switching circuit controls the jet power circuitry.

9. <u>Shift signal generator</u> - The output of this generator is used to trigger the sequence control circuit at a constant rate.

10. <u>Jet power circuits</u> - As many as 96 jets may be used and the control circuits must be capable of controlling one jet at a time.

11. <u>Oscillatory power supply</u> - Experimental results indicate that an oscillating power supply is needed to increase the astronaut's pattern

recognition level. Consequently, this block is needed to provide a cyclic air pressure source.

Section 7

CABIN LEAK DETECTION

7.1 SUMMARY

An attractive application of fluid amplifiers appears to be a leak detector for signaling the astronaut in the event of cabin leakage. Two general arrangements are envisioned. In one, fluid amplifiers are used to sense and amplify the flow rate of the makeup flow. High flow rates indicate steady-state leakage is occurring. A second approach is to sense the rate-of-change of the cabin pressure. This type of sensor will detect and indicate any abrupt change in cabin pressure caused by sudden leakage. A missing link in the devices is a transducer for providing a visual or audible signal from a fluid signal.

7.2 LEAK RATE DETECTOR

The basic concept is illustrated in Figure 7-1. The makeup flow passes over a step which is manifolded to one control port of a proportional amplifier. The ejector action, caused by the fluid shear at the step, will lower the pressure on control port C1. Control port C2 is vented to the cabin ambient. Thus, as maekup flow increases the fluid jet in the amplifier is deflected by the lowered pressure in C1. The signal in control port C1 will be very small since small makeup flow rates are of interest. The supply pressure, must also be small to provide good amplifier performance. A logical source to power the amplifiers is the cabin blower. The output from the amplifier would be at a relatively low pressure level. Although the control and supply pressures used in this application are small values, they are within the state-of-the-art of fluid amplifiers. Good performance has been measured on proportional amplifiers with supply pressures as low as 0.075 psig and with signal pressures as low as 0.005 psi (0.1 inch water). These pressure values are by no means considered as a lower limit; wall attachment of a jet has been observed at supply pressures down to 10^{-4} psi.

Other forms of the pickup or flow sensor can be used as shown in Figure 7-2. A modified form of the ejector (Figure 7-2A), is a reverse pitot. Another
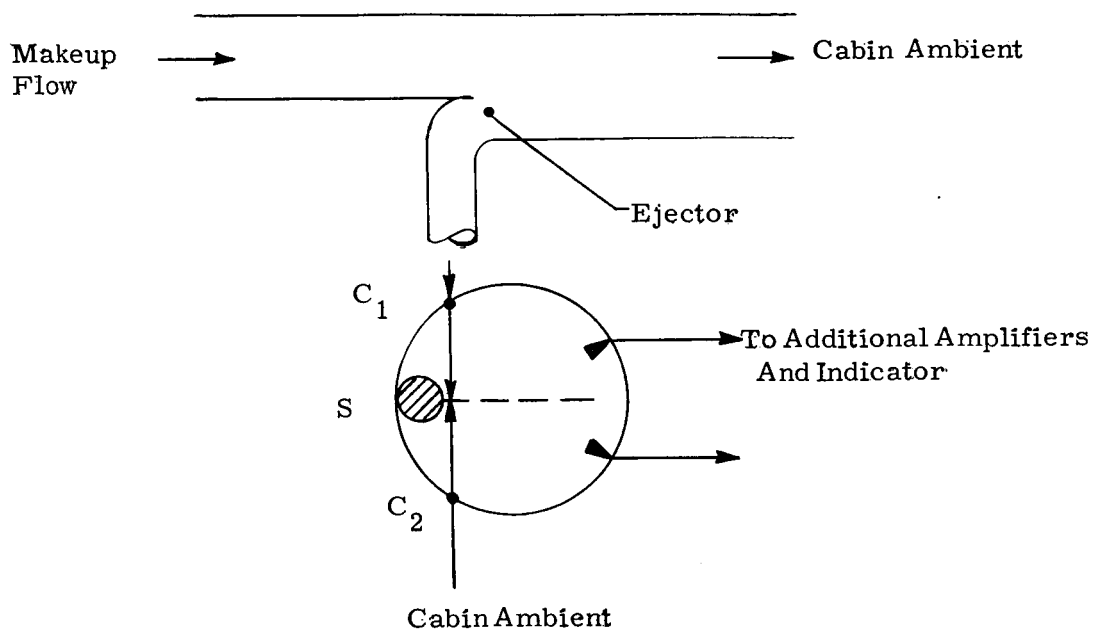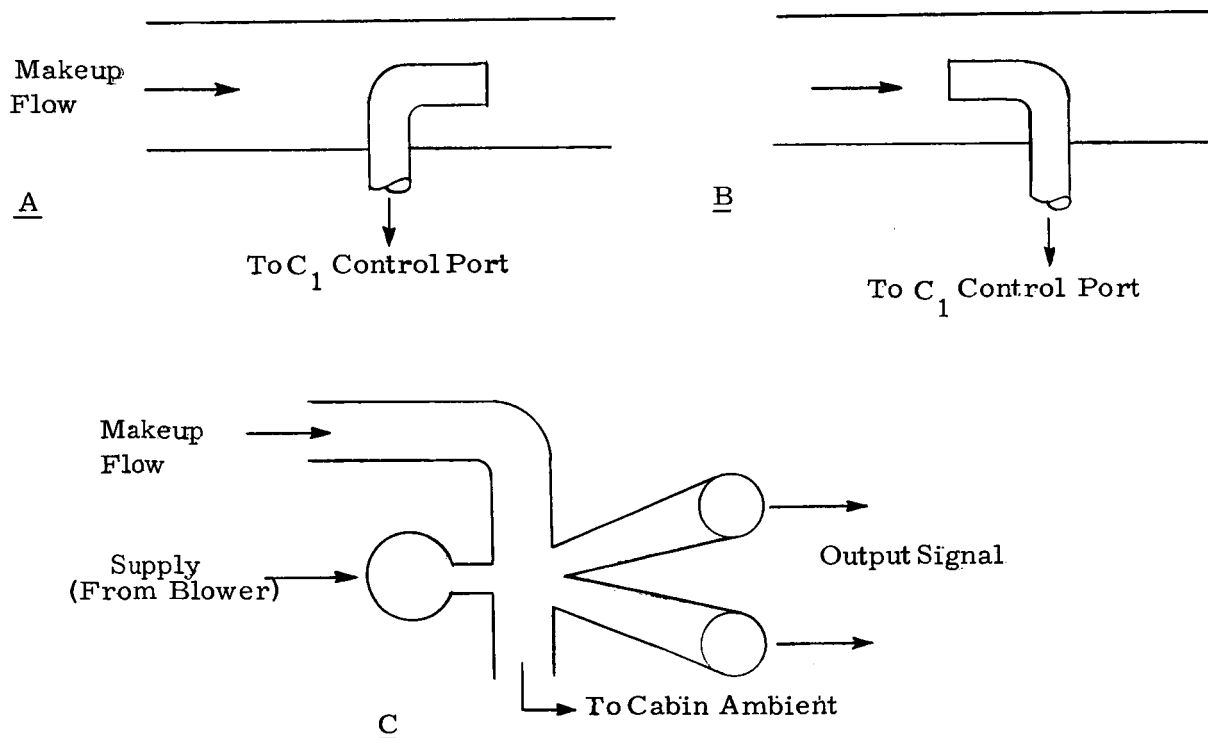
Figure 7-1. Leak Rate Detector.

Figure 7-2. Alternate Arrangements of the Leak Rate Detector.

arrangement is the forward pitot (Figure 7-2B). This arrangement uses impact or the dynamic head to raise the pressure in the sensor line instead of a pressure decrease, as described above. A third possibility (Figure 7-2C) is to pass the entire makeup flow through the control port of the fluid amplifier before it reaches the cabin ambient. This amplifier would have to be specifically designed to avoid excessive restriction of the makeup flow. Although proportional fluid amplifiers have been illustrated, digital amplifiers could be used. The first stage would have memory and could be adjusted to a predesignated threshold so that when the makeup flow reached a critical level, the amplifiers would switch and would provide a visual indication. The indication would be digital rather than proportional, however.

Another possible arrangement for sensing makeup flow is illustrated in Figure 7-3. The momentum of the makeup flow is used to deflect a series of jets. The jets are powered from the cabin blower. When makeup flow is small the jets impinge on the receivers, and pressure recovery in all the receivers is maximum. The receivers are arranged, however, with increasing axial distance between them and the jet nozzles as shown in Figure 7-3. This arrangement results in increasing sensitivity to the momentum of the makeup of flow, i. e., the greater the nozzle-receiver distance the greater the sensitivity. Several nozzle-receivers are operated in parallel, each capable of triggering a digital amplifier connected to the jet receiver. Outputs from the fluid switches would be fed into logic circuitry to provide a digitized output. The digital amplifier connected to the jet receiver with the greatest nozzle-receiver spacing would be triggered first and would set the threshold or sensitivity desired.

An alternate form of the arrangement (Figure 7-3) would use turbulence amplifiers. The advantage of their use may be increased sensitivity. The turbulence amplifier principle is based on the fact that a laminar jet impinging on a receiver will have a very high recovery while a turbulent jet has very low recovery. Turbulence amplifiers can be used in place of the nozzle-receivers shown in Figure 7-3. The receiver with the greatest nozzle receiver spacing would be adjusted to the axial distance just ahead of the point where the jet

To Blower Powered
Amplifiers and Readout
Logic

Receivers

① ② ③
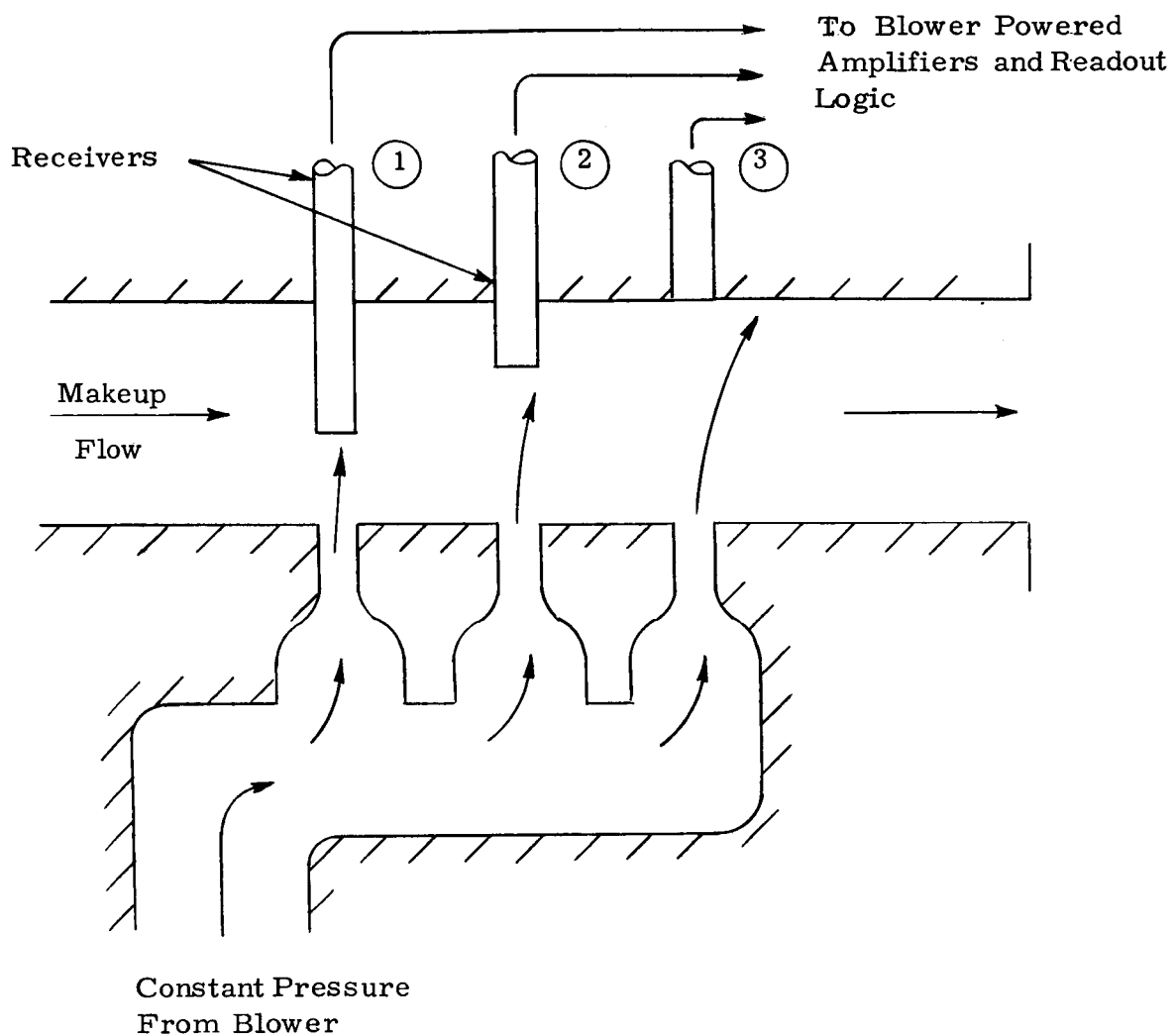
Makeup

Flow

Constant Pressure
From Blower

Figure 7-3.   Jet Makeup Flow Sensor.

becomes turbulent with no external disturbance. This is the most sensitive sensor and establishes the threshold. The other nozzle-receiver combinations are arranged with less axial spacing and thus require a higher level of disturbance (or makeup flow) to trigger them. Readout would be performed in the manner described in the preceding paragraphs. The more sensitive nozzle-receivers should be placed downstream so that when their jets become turbulent they will provide minimum disturbance to the upstream sensors.

7.3 SENSOR FOR PRESSURE RATE

The rate of change of the cabin pressure may, in some instances, be a better indication of cabin leakage than sensing makeup flow. A fluid amplifier which provides an output proportional to the rate of change of the pressure applied to the input is illustrated in Figure 7-4. The input signal, the cabin ambient pressure, is fed to both control ports of a proportional amplifier. The branch going to the C2 control port passes through a restrictor-volume combination which results in an "R-C" lag. Thus at steady-state no output signal (pressure difference between 01 and 02) occurs. When the input pressure is changed, however, an output signal proportional to the input pressure rate of change, is obtained, since the signal at C2 is delayed. The circuit functions as a high pass filter. The output from the circuit would be amplified with fluid devices to the level required to drive the pneumatic/visual transducer.

$$\text{Output} \ = \ K \, \frac{dP_c}{d_t}$$
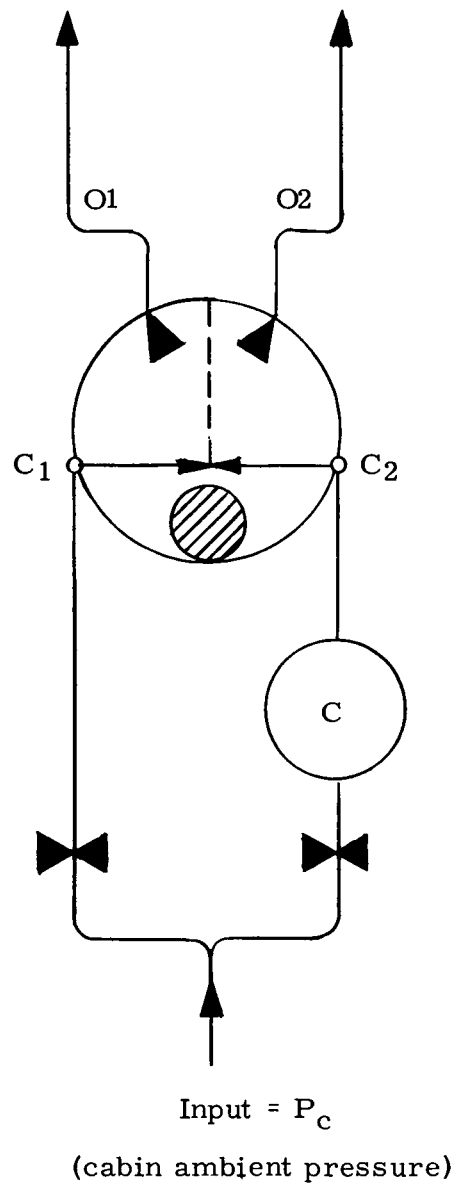
Figure 7-4. Sensor for Pressure Rate

Section 8

APPLICATION OF FLUID AMPLIFIERS TO LIQUID PROPELLANT ROCKET ENGINES

The use of fluid amplifiers in propulsion systems is somewhat unique in that, in many instances, the end item to be controlled is a fluid. In many applications, applicability of these devices is enhanced because the fluid to be controlled is either at a relatively high or very low temperature and control by conventional means is difficult. High temperatures are experienced in secondary injection attitude control systems; low temperatures are experienced in control of cryogenic fuels. This section briefly summarizes possible applications of fluid amplifiers for liquid rocket propulsion systems. Control concepts include analog as well as digital devices.

Government agencies, as well as private companies, presently are engaged in the development of fluid amplifier control elements for rockets. Two of these applications are summarized in Figure 8-1. Gas bled from the gas generator responds to input signals from the indicated servo control valves and is employed both in roll control as well as engine thrust vector pitch and yaw functions. Other gas sources that might be available on the engine include the turbine exhaust as well as combustion gases from the main thrust chamber assembly.

Reference 8-1 reports the results of a program wherein fluid amplifiers are employed to control solid propellant gases used in attitude control of an experimental missile. The Pratt & Whitney Aircraft Division (Florida), United Aircraft Corporation, has been working on secondary injection with fluid amplifiers for about two years. A recent RFQ No. CRSD-2082 issued by NASA Lewis Research Center, Cleveland, Ohio, was concerned with proportional fluid amplifiers for secondary injection of hydrogen rich combustion gases at flow rates up to five pounds per second at 500 psia.

Ref. 8-1 Experimental Design of a Fluid Controlled Hot Gas Valve, Report No. RE TR-62-9, U.S. Army Missile Command, Redstone Arsenal, Alabama, 31 Dec. 1962.
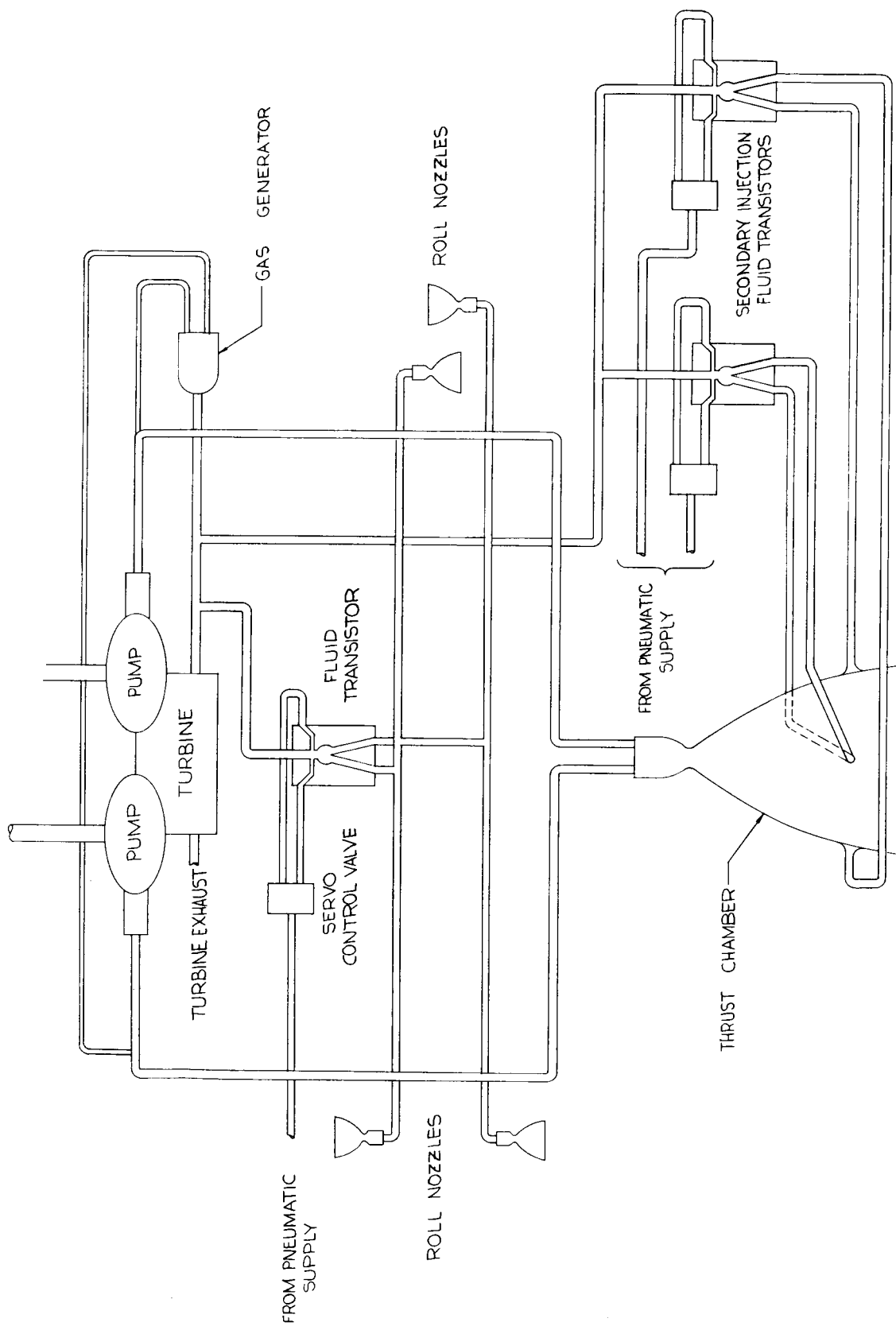
Figure 8-1. Application of Fluid Amplifiers for Roll Control and Secondary Injection.

Figure 8-2 illustrates how proportional fluid transistors may be employed in chamber pressure and reactant ratio controllers. The reactant ratio controller works on a null balance principle employing pressure signals taken off upstream of cavitating venturis to sense the flow rate. For operation about some nominal reactant ratio (R_{wn}) and pressure (P_n), it can be shown that a change in reactant ratio is related to changes in oxidizer and fuel pressure by the following linear relation

$$\Delta R_w = \frac{R_{wn}}{2\,P_n}\left[\Delta P_o - \Delta P_f\right]$$

The first stage amplifier (A) receives the differential pressure ($\Delta P_o - \Delta P_f$) transmitted by liquid fuel (isolated from the oxidizer by means of an accumulator) across its input ports, amplifies this signal, and compares it to a fluid signal representing a desired (not necessarily constant) reactant ratio. This error is applied to the final fluid amplifier (B) which acts as a diverter valve bypassing fuel to the pump suction. The chamber pressure control operates in a similar manner. Chamber pressure, transmitted through suitable accumulators, is compared to a requested value, and the difference signal diverts the oxidizer and fuel flows either to the pump suction or to the gas generator to increase the turbine power.

The latter two control schemes can also be implemented by means of vortex valves, acting as variable restrictors in the main propellant and gas generator feed lines. In addition, other pressure regulating applications (as presented in the chamber pressure controller) are apparent. A pneumatic gas regulator can be constructed by considering the "desired P_c" signal as a regulator reference and "P_c" as the regulated pressure fed back from the load. Additional schemes could utilize cryogenic fluids in conjunction with cryogenic boilers for tank pressurization.

Although the preceding discussion has been concerned with analog elements, applications also appear practical for digital elements. Engine sequencers driven by fluid timers can be employed to sequence various pre-selected events. Various gating and coincidence circuits applicable to engine

Figure 8-2. Application of Proportional Fluid Amplifiers in Chamber
Pressure and Reactant Ratio Controllers.

8-4

operation can be utilized in conjunction with information previously stored in shift registers. As an example, some engines have used ignition time gates such that if indication of combustion (as initiated by an ignitor) is not received by a certain time the engine proceeds to a shutdown condition. Other operations, such as pressure sequencing of one event from the successful completion of a previous event, can be accomplished in some cases with the actual fluid. Thus, the need for intermediate transducers and appropriate pilot valves is eliminated. Malfunction decisions can also be made based on fluid logic.

Section 9

RELIABILITY

9.1 SUMMARY

The most popular reason given for considering fluid amplifiers and logic for space applications is "reliability." The absence of moving parts and the apparent tolerance of adverse environments give intuitive confidence in their reliability. The facts are, however, that the reliability of fluid elements has not been definitely established and is still a matter for conjecture and personal opinion. Only one technical paper (Ref. 9-1) is known to the authors which attempts to deal with this problem quantitatively.

In order to get a basis for considering reliability as a suitable criterion for selecting applications acceptable within the guide-lines for Phase II, a brief comparative study was made of several possible implementations of the digital integrator discussed in Section 4 "Computation and Logic (Digital Integrator)", of this report. The fluid circuits were compared numerically to their electronic counterpart. The simplest electronic circuit, the serial, was used since its speed would be higher than that of any of the fluid implementation.

9.2 ASSUMPTIONS

Since there has been no reported data on fluid amplifier reliability work, it was necessary to assume critical modes of failure and their rates of occurrence. Some assumed values for these data are listed in Reference 9-1, but the values listed below are believed more realistic. Factors for scaling both the electronic and the fluid equipment to severe vibration and radiation environment were taken from this reference. Failure rates for electronic

Ref. 9-1 Fox, H. L., "A Comparison of the Reliability of Electronic Components and Pure Fluid Amplifiers", Proceedings of the Fluid Amplification Symposium, October 1962, Vol. 1. DOFL, Washington, D.C.

equipment, under standard MIL Specification conditions, were taken from Reference 9-2.

Modes of failure and failure rates for fluid amplifier circuits were predicted to be:

1. Contamination -- plugging resulting from the introduction of foreign material. Failure rate $0.01/10^6$ hours.

2. External connections -- failure of the pneumatic connections attached to the integrator circuit. Multiple power supply and clock connections are assumed internally manifolded. Failure rate $0.04/10^6$ hours.

3. Crossport leakage -- critical leakages occurring at the cover and circuit channels, such as between the power supply and the control channel. One crossport leakage factor was assumed for each element. Failure rate $0.01/10^6$ hours.

9.3 CALCULATION OF DIGITAL INTEGRATOR FAILURE RATE

9.3.1 SERIAL FLUID INTEGRATOR

The total number of fluid elements (Table 9-1) is 87. The number of external connections required (Figure 9-1) is nine. If one contamination factor per external connection is assumed, the estimated failure rate is:

Crossport leakage	0.01 x 87	=	0.87
External connection	0.04 x 9	=	0.36
Contamination	0.15 x 9	=	1.35
			2.6 failures/10^6 hours

If one contamination factor per element is assumed, the failure rate becomes:

Crossport leakage	0.01 x 87	0.87
External connection	0.04 x 9	0.36
Contamination	0.15 x 87	13.0
		14 failures/10^6 hours

Ref. 9-2 Earles, D. R., and Eddins, M. F., "Failure Rates" Reliability Engineering Data Series, The Avco Corporation, April 1962.

SERIAL INTEGRATOR
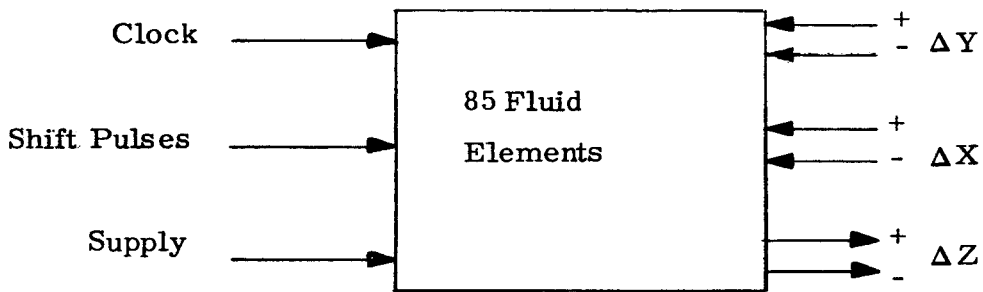
PARALLEL INTEGRATOR
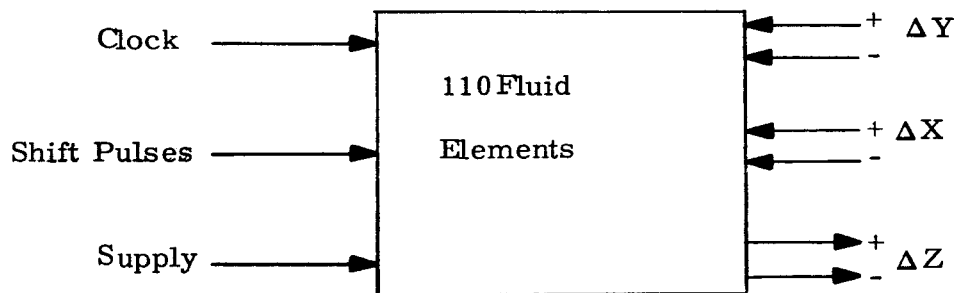
Figure 9-1. Digital Integrator Blocks.

<div align="center">

TABLE 9-1
Serial Fluid Digital Integrator Element Count

</div>

"Y" Register		Pulse Ports	P. S. Ports
Flip-Flop	10	15	11
AND/EX-OR	20		
OR/NOR	1		
"Y" Adder"			
Flip-Flop	3	6	5
AND/EX-OR	5		
OR/NOR	2		
"R" Register		Pulse Ports	P. S. Ports
Flip-Flop	10	3	11
AND/EX-OR	20		
OR/NOR	1		
"R" Adder			
Flip-Flop	3	9	7
AND/EX-OR	9		
OR/NOR	3		

<div align="center">

87 elements

</div>

9.3.2 PARALLEL FLUID INTEGRATOR

The computation of failure rates is performed in a manner similar to the above calculations, except that 110 elements are considered (Table 9-2); the number of external connections is still 9 (Figure 9-1). The results are as follows:

One contamination factor per external connection -- integrator failure rate = $2.8/10^6$ hours.

One contamination factor per element -- integrator failure rate = $18/10^6$ hours.

TABLE 9-2

Parallel Fluid Integrator Element Count

"Y" Register and Adders

Flip-Flop	13
AND/EX-OR	31

"R" Register and Adders

Flip-Flop	13
AND/EX-OR	52
OR/NOR	1

TOTAL

Flip-Flop	26
AND/EX-OR	83
OR/NOR	1
	110 elements

9.3.3 SEMICONDUCTOR MECHANIZATION

Since the operating speeds of semiconductor circuits are very high, a single mechanization (that of the serial integrator) will serve the range of iteration rates being considered.

A compilation of the total number of logic circuits is shown in Table 9-3. The logic diagrams of the semiconductor serial integrator are shown in Figures 9-2 through 9-6. Flip-Flop and NOR failure rates (-40°F to 140°F) are computed as follows:

Per Flip-Flop		Per NOR	
2 transistors	0.6×10^{-6}	1 transistor	0.3
8 resistors	0.4	6 resistors	0.3
20 joints	0.4	15 joints	0.3
	$1.4/10^{6}$ hours		$0.9/10^{6}$ hours

Failure rate for the digital integrator then is calculated as:

26 Flip-Flops x 1.4   36.4

19 OR's x 0.9   17.1

35 modules x 10
connections x 0.02   7.0
                    ─────────
                    60 failures/10^6 hours

TABLE 9-3

Semiconductor Element Count

"Y" Register		Connections
Flip-Flop	10	156
"Y" Adder		
Flip-Flop	3	186
NOR	9	
"R" Register		
Flip-Flop	10	156
"R" Adder		
Flip-Flop	3	201
NOR	10	

26 Flip-Flops

19 NOR's

699 Connections

9.4   CONCLUSIONS

The above failure rates are based on standard MIL specification environmental conditions. Where radiation and high vibration are involved, their effect on reliability is accounted for by the factors shown in Table 9-4.

TABLE 9-4

Summary Table
(Failures Per 10^6 Hours)

Environment	Fluid Amplifier Serial	Parallel	Semiconductor
Standard flight vehicle	3 to 14	3 to 18	60
Missile vibration(Ref. 9-1)	30 to 140	30 to 180	54,000
Nuclear reactor vicinity (Ref. 9-1)	30 to 140	30 to 180	60,000

The data in Table 9-1 indicate that the fluid implementation probably is somewhat more reliable than the electronic one at standard MIL specification conditions. The assumptions made for the fluid elements need to be verified, but are probably conservative. The real reliability advantage of the fluid equipment would appear to be where there are severe environmental requirements. This brief study did not consider relative reliability for "shelf life", but it is likely the fluid elements would be somewhat superior to the electronic ones in this respect.

The major conclusion that can be drawn is that there is a reasonable possibility of high reliability for the fluid elements, even on a calculated numerical basis, and that this area is in dire need of further definition and investigation.

Figure 9-2. Digital Integrator Block Diagram.
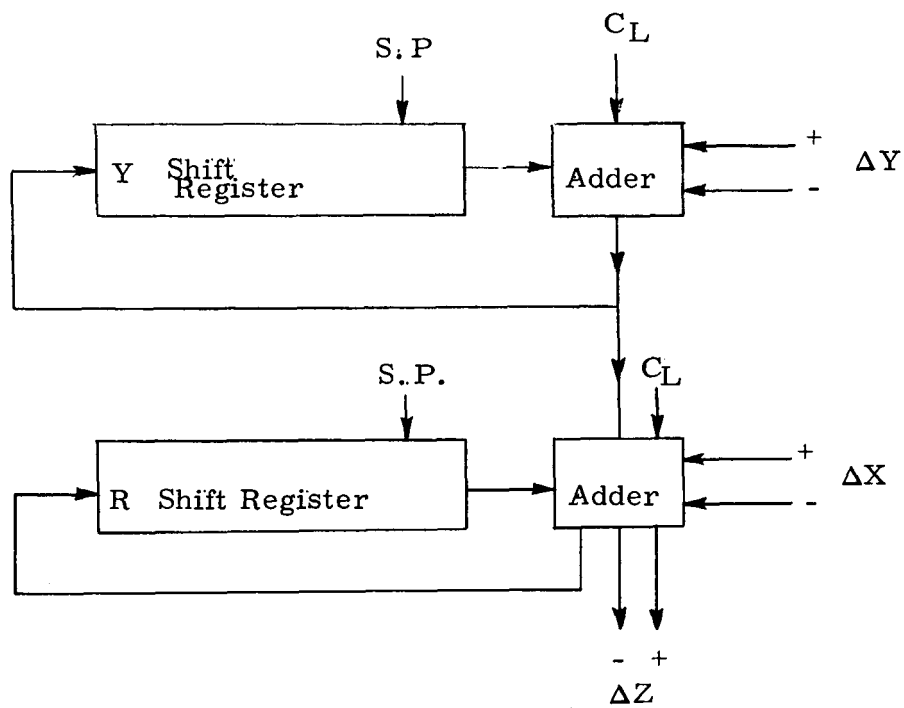
S.P. = Shift pulse

C_L = Clock pulse
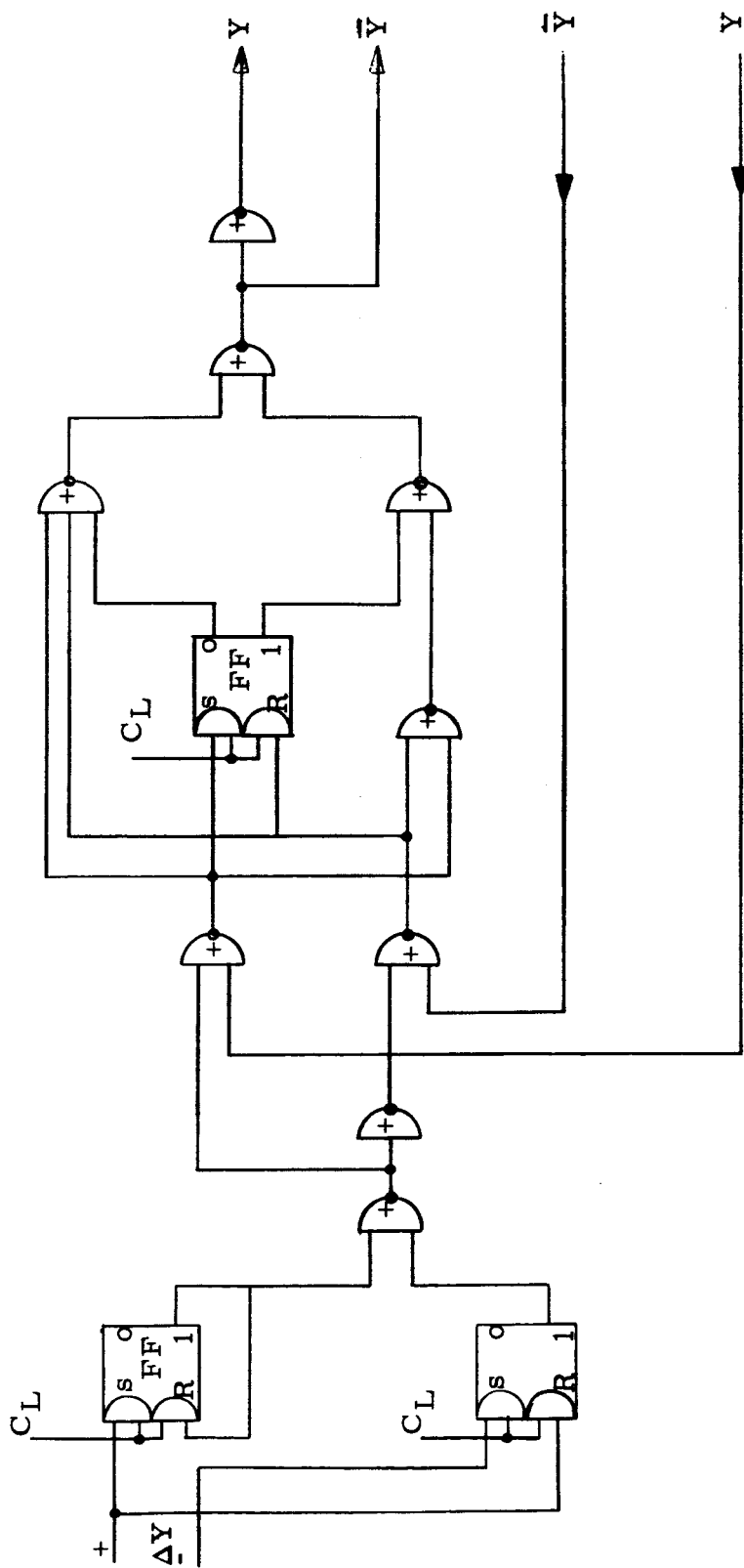
Figure 9-3. "Y" Serial Semi-Conductor Adder.
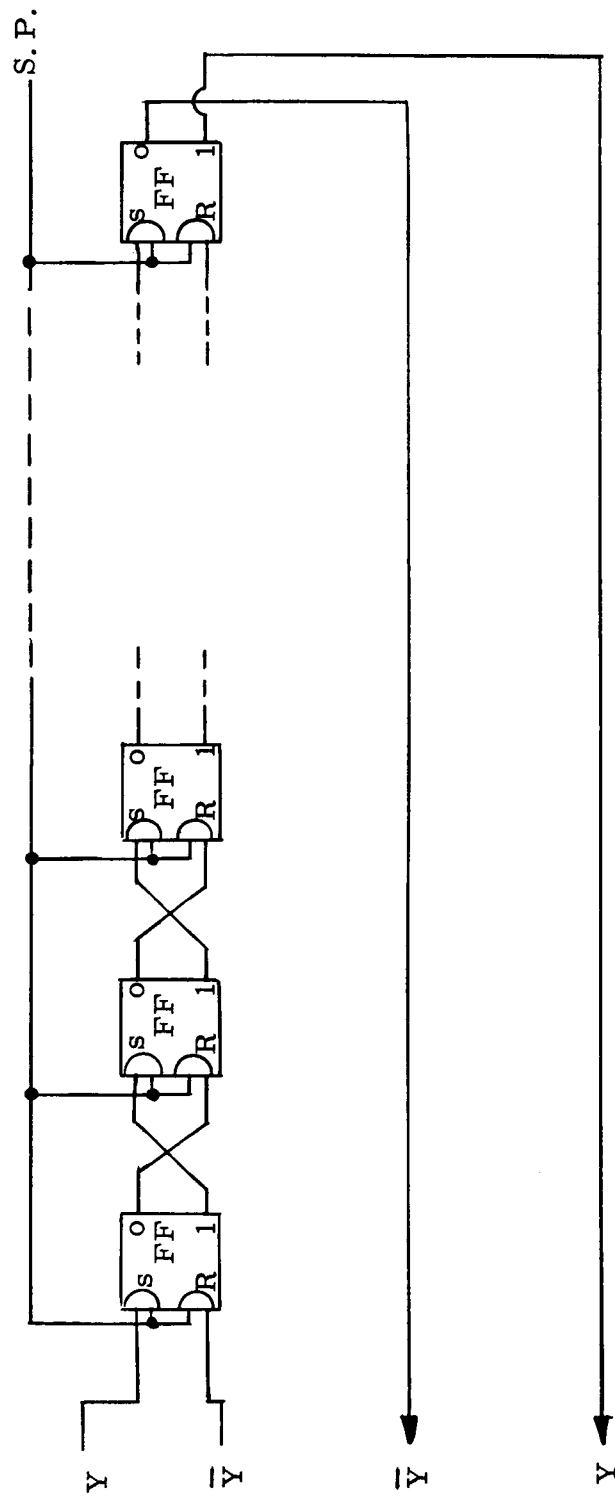
Figure 9-4. "Y" Shift Register.
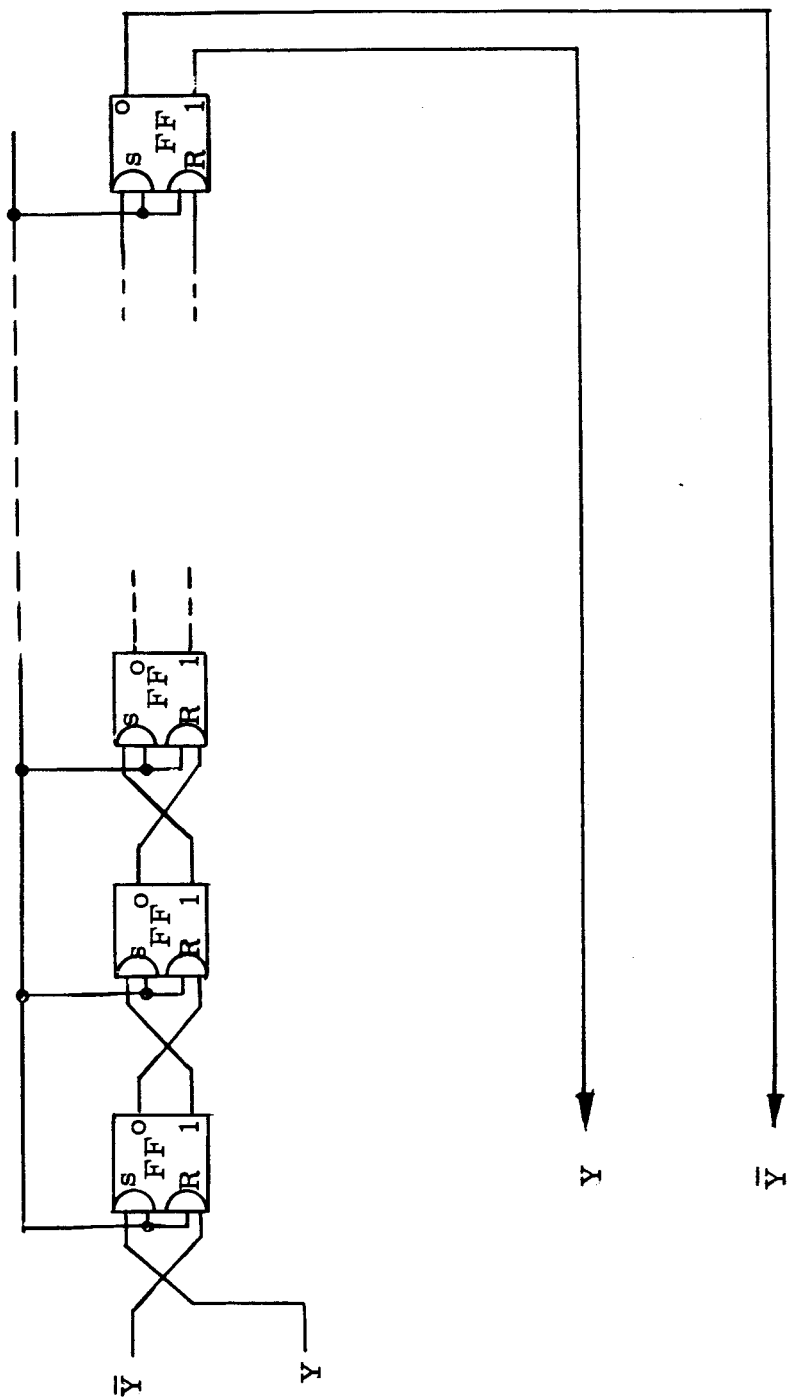
Figure 9-5. "R" Shift Register

9-11
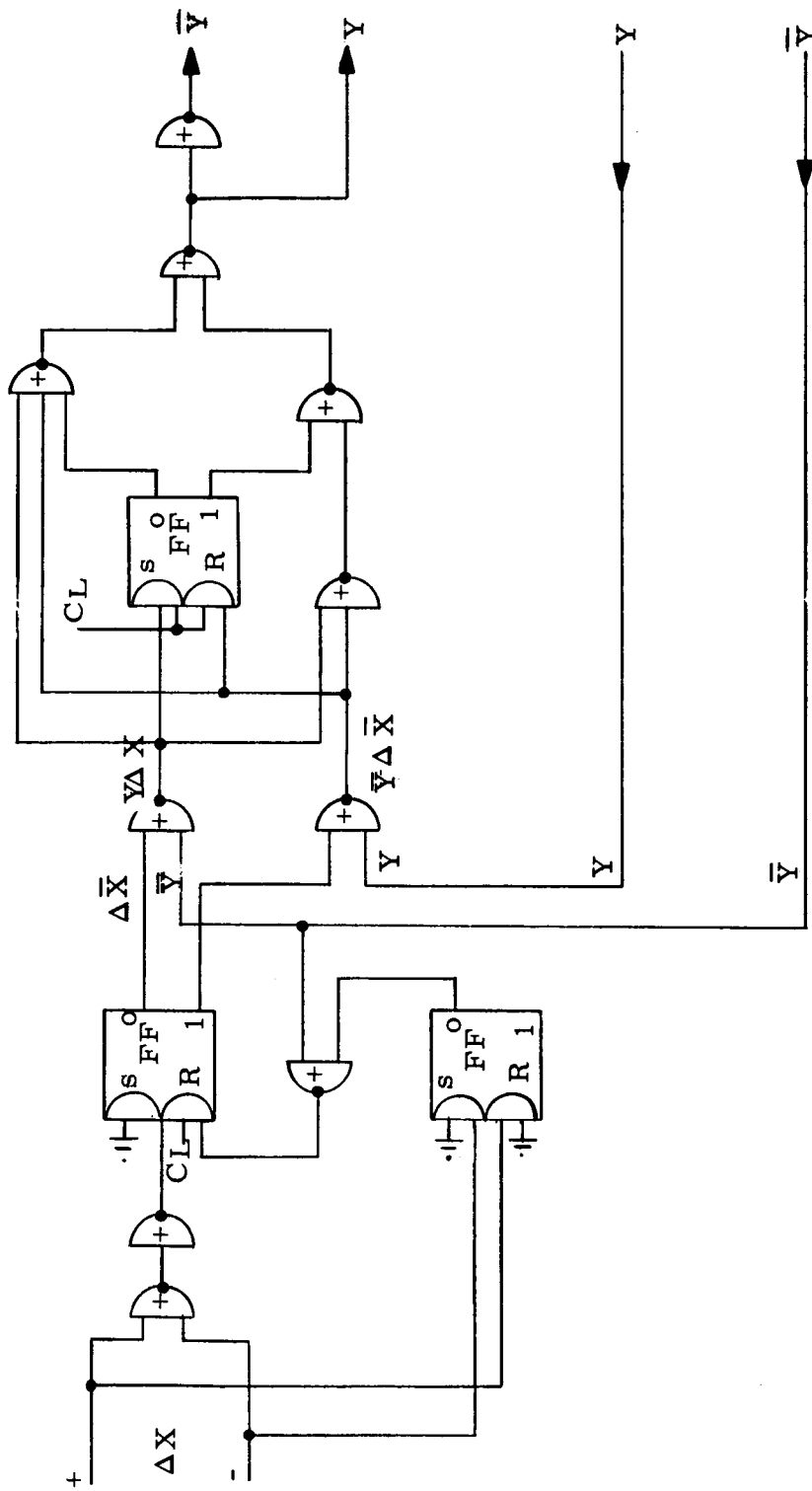
Figure 9-6. "R" Serial Adder

9-12

Section 10

POWER CONSUMPTION AND POWER SOURCES

For fluid amplifier applications, such as digital computation requiring large numbers of elements, power consumption and power sources are a very important consideration, especially where a fluid power source is not already on board. The lifeboat computer discussed in Section 3, "Space Station Lifeboat," of this report, for example, would require 6,000 to 13,000 elements depending on the system chosen. Such systems may be impractical because of power consumption and the lack of power sources, unless these areas receive adequate attention early in the development phase. The discussion below summarizes the material on power supplies presented in the Phase I report, and points out some "order of magnitude" characteristics of fluid element power consumption and fluid sources.

10.1 POWER CONSUMPTION

When a typical fluid amplifier is powered with compressible fluids, little actual "power" consumption occurs; the flow process actually approaches a throttling process. No work is extracted from the system (such as with pistons or expanders). In ideal throttling, no heat transfer occurs and all the energy at the source would leave at the exhaust; the inlet and outlet temperatures would be the same. Power consumption in this case can be thought of in terms of the work necessary to compress the gas to the supply pressure. Figure 10-1 shows a calculated curve for power consumption on this basis, using air as the fluid. A 0.010 by 0.010 inch nozzle operating at 0.1 psi, for example, would require a 2×10^{-5} watts per square mil, or two milliwatts. This is the equivalent power consumption required for a single element, in terms of the work of supplying flow, to produce a 0.1 psi drop across the nozzle.

In the case of ideal incompressible fluids, a pressure drop results in an enthalpy drop with no temperature change and therefore represents a true power consumption. Figure 10-1 shows a calculated power consumption curve

10-1
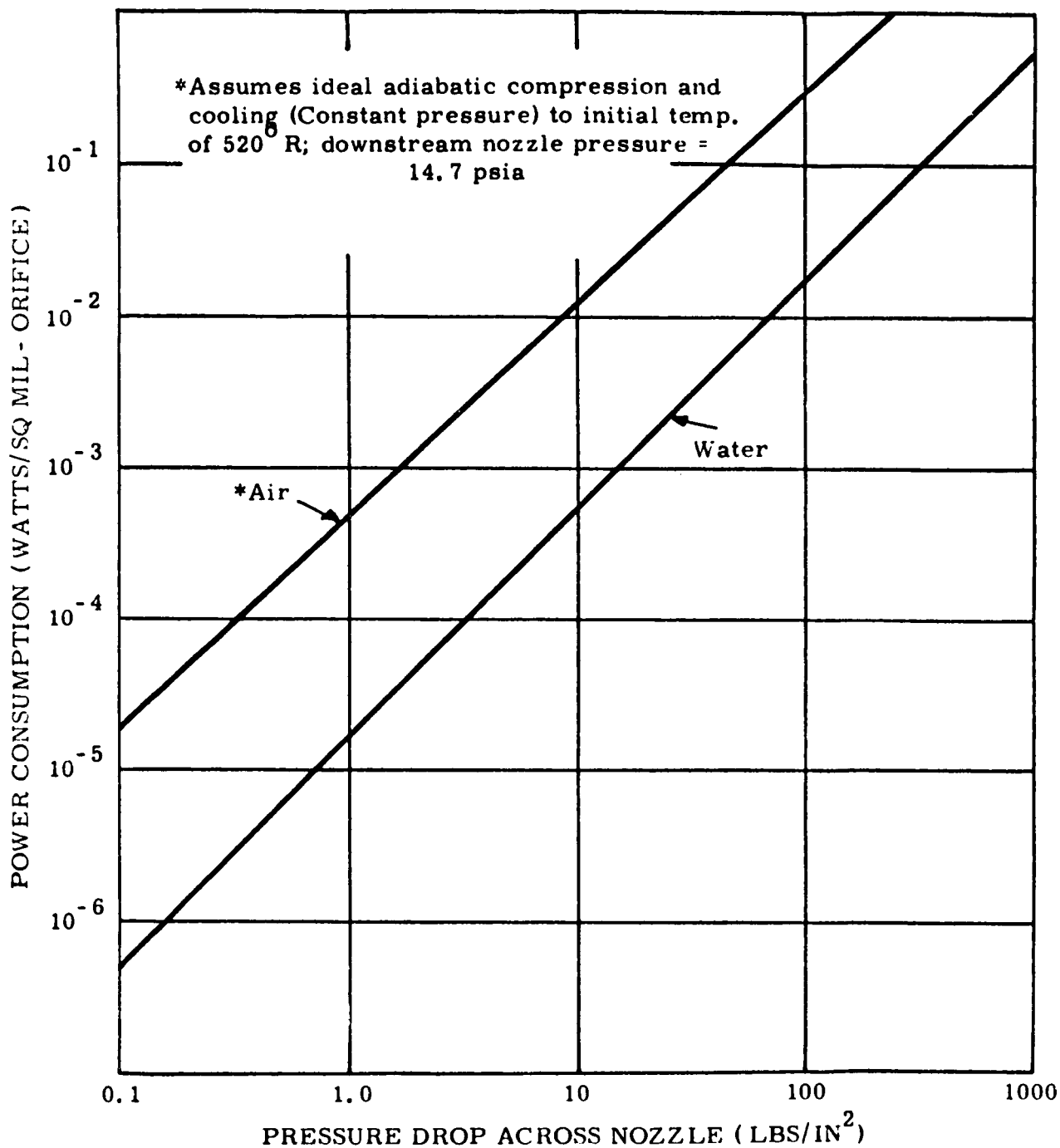
Figure 10-1 - Calculated Nozzle Power Consumption

for water. The 0.010 by 0.010 inch nozzle at 0.1 psi in this case consumes 0.05 milliwatt of power.

10.2 POWER SOURCES

Power sources for fluid amplifier systems can be categorized into two general classes:

> Parasitic sources
>
> Self-contained

Fluid amplifiers using parasitic supplies make use of an existing fluid source, and two possible flow arrangements exist. The most common is to simply draw additional flow from the existing source to feed the fluid amplifier system and then vent the exhaust flow to a sump or the ambient. In the second arrangement, identified as the "through-flow" type, the fluid passes through the fluid amplifier system before it flows to the equipment originally requiring the fluid source. The fluid amplifier circuit results in an additional pressure drop but it often can be small compared to the pressure drop across the other equipment. For example, pneumatic power sources often utilize high pressure storage (3,000 to 6,000 psi) with regulators to drop the pressure by a factor of 10 to 100. A fraction of this pressure drop could be used to power fluid amplifier devices.

Self-contained sources generally can be identified as finite duration devices, or continuous devices. Continuous devices may range from mechanical, or ram, compressors to thermally powered loops using no moving parts. The latter seem more appropriate for fluid amplifier systems since they should have advantages similar to fluid amplifiers, i.e., high environmental tolerance and potential reliability. The need for a thermal loop, continuous power source must first be established by considering the specific application and the possible use of a finite duration power source.

Finite duration sources appear to be the simplest and most reliable. Two possible types are chemical gas generators and fluid storage, such as high-pressure gas bottles or a liquid in an accumulator. A fluid amplifier

thrust vector control using a solid propellant gas generator is presently under development at the Redstone Arsenal. Longer operating times could be obtained with the use of liquids such as hydrogen peroxide or hydrazine. High-pressure gas bottles are the simplest and most reliable self-contained power source, but for long operating times the size of the bottles, or tanks, may be prohibitive. To learn more about the possible application areas, the characteristics of stored gas power sources were analyzed. The results provide the basis for some insight into the practicability of using a stored gas source for fluid amplifier systems.

10.2.1 STORED GAS FLUID SOURCE

The arrangement considered and nomenclature are shown in Figure 10-2. Initially, the tank is charged with a given quantity of gas:

$$W_T = \frac{P_T V}{RT}$$

The operating duration of interest is minutes to hours and days so that isothermal flow is assumed. At the end of the operating time, the pressure in the tank finally drops to the fluid-amplifier supply pressure and the weight of the gas in the tank at this time is:

$$W_f = \frac{P_S V}{RT}$$

The total gas weight which flows through the fluid amplifier circuit is the difference between the initial and final gas weights in the tank and is equal to the product of the gas flow rate, w, and the duration of the operation, D, as follows:

$$W_T - W_f = (P_T - P_S) \frac{V}{RT} = wD$$

Generally $P_T >> P_S$ so

$$wD = \frac{P_T V}{RT} \tag{10-1}$$

For simplicity the flow rate is computed from incompressible relations since the supply pressure drop will be small. Thus

NOMENCLATURE:

A = fluid amplifier
    power nozzle area

D = operating time

g = gravitational constant

P_S = fluid amplifier
    supply pressure (absolute)

ΔP = power nozzle pressure drop

P_T = initial tank pressure

R = gas constant

T = gas temperature

V = tank volume

W_T = initial gas weight in tank

W_f = final gas weight in tank

w = weight flow rate to fluid
    amplifier system

Initial Conditions
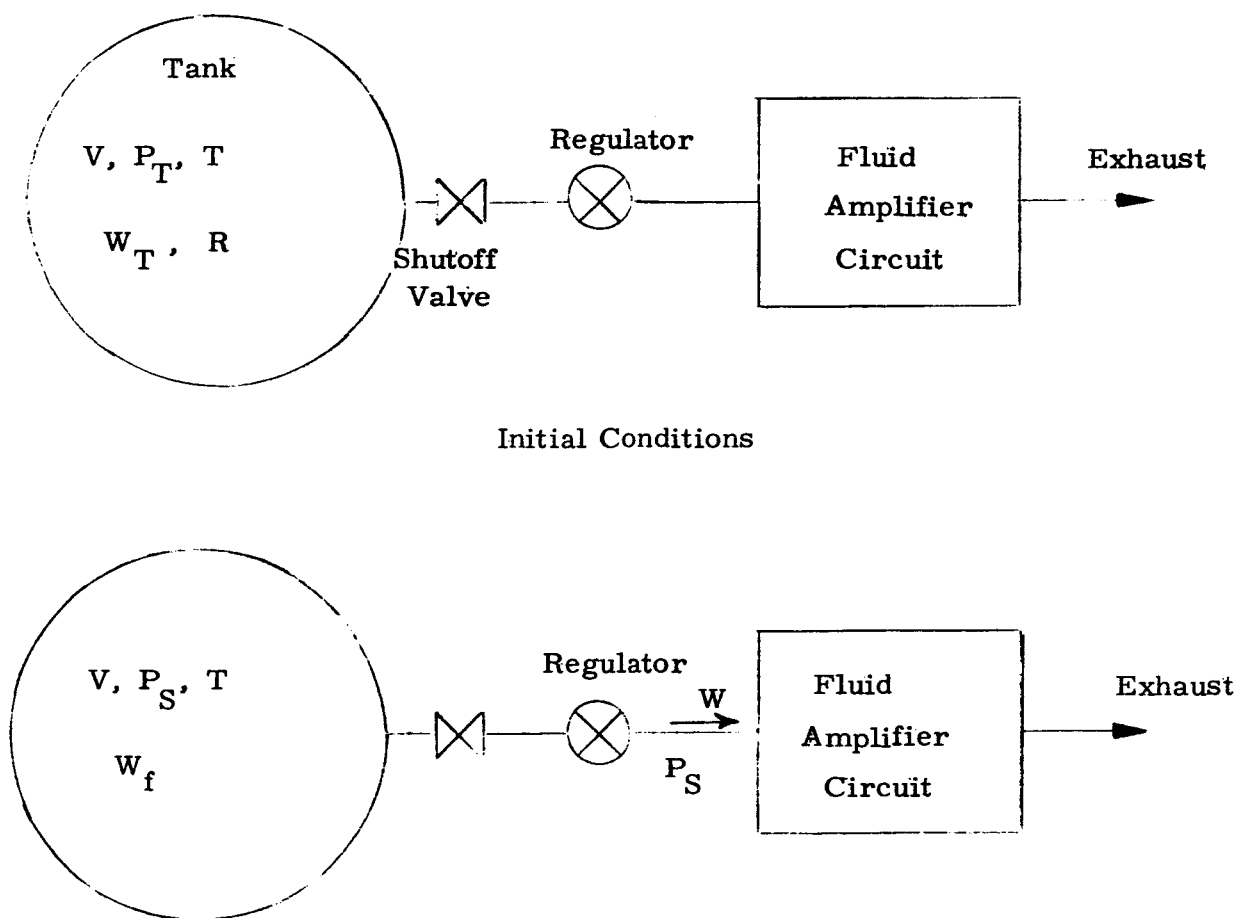
Figure 10-2. Nomenclature and Schematic Diagram of Stored Gas System.

$$W = \rho A v$$

$$\text{Where: } v = \sqrt{2g\,\frac{\Delta P}{\rho}}$$

$$\text{and } \rho = \frac{P_S}{RT}$$

$$\text{Then: } \quad w = A\sqrt{\frac{2g}{RT}}\;\sqrt{P_S\,\Delta P} \tag{10-2}$$

Equating 10-1 and 10-2 to eliminate w, and solving for D, the desired relation is obtained as:

$$D = \frac{V\,P_T}{A\left[2g\,R/T\,P_S\,\Delta P\right]^{1/2}} \tag{10-3}$$

From this relation it can be seen that the operating time is, D, is:

1. Directly proportional to the tank volume

2. Directly proportional to the gas storage pressure

3. Inversely proportional to the power nozzle flow area

4. Inversely proportional to the square root of the gas constant and temperature; hence heavier gases at low temperatures are advantageous

5. Inversely proportional to the square root of the nozzle supply pressure and pressure drop; nozzle pressures are of less significance than initial storage pressure.

The relations between tank volume, initial storage pressure, and operating time under typical conditions with nitrogen gas are illustrated in Figure 10-3 and 10-4. The effect of varying gas content, temperature, supply pressure, and pressure drop on required tank volume can be seen in Figure 10-5. The curve is normalized for simplicity. The effect of doubling the temperatures, for example, can be seen to require 1.41 times the volume to provide the same operating time with all other conditions remaining constant.

CONSUMPTION FOR 100 NOZZLES

Figure 10-3. Tank Volume Versus Operating Time.
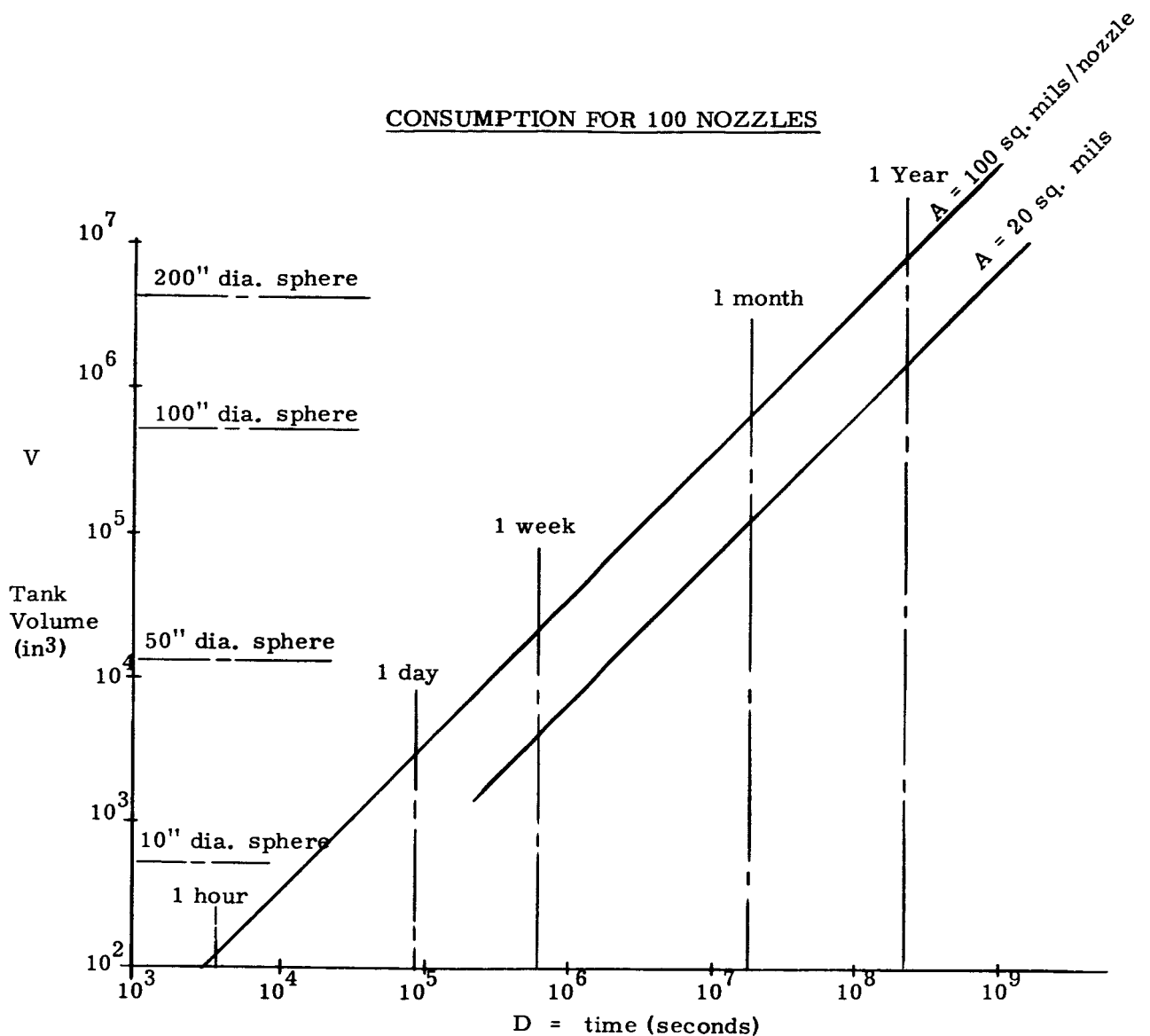
$$D = \frac{V_T \, P_T}{A} \left[2g \, RTP_S \, \Delta P \right]^{-1/2}$$

P_T = 600 psi

T = 530° R

P_S = 15 psia

ΔP = 0.1 psi

R = (N$_2$)

CONSUMPTION FOR 100 NOZZLES
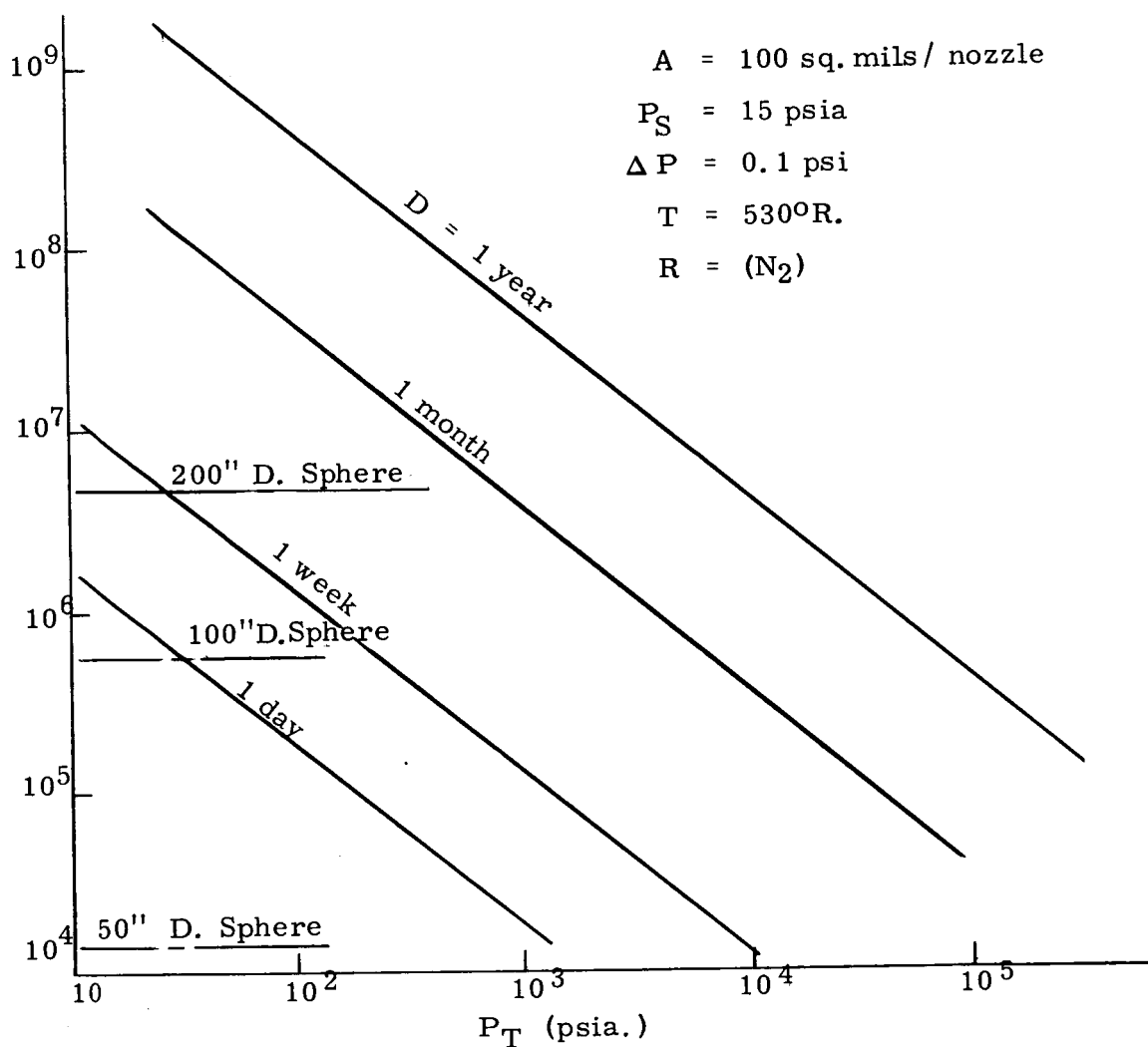
$$V = \frac{DA}{P_T} \left[2g \, RTP \, P_S \, \Delta P \right]^{1/2}$$

Figure 10-4. Tank Volume Versus Initial Storage Pressure.
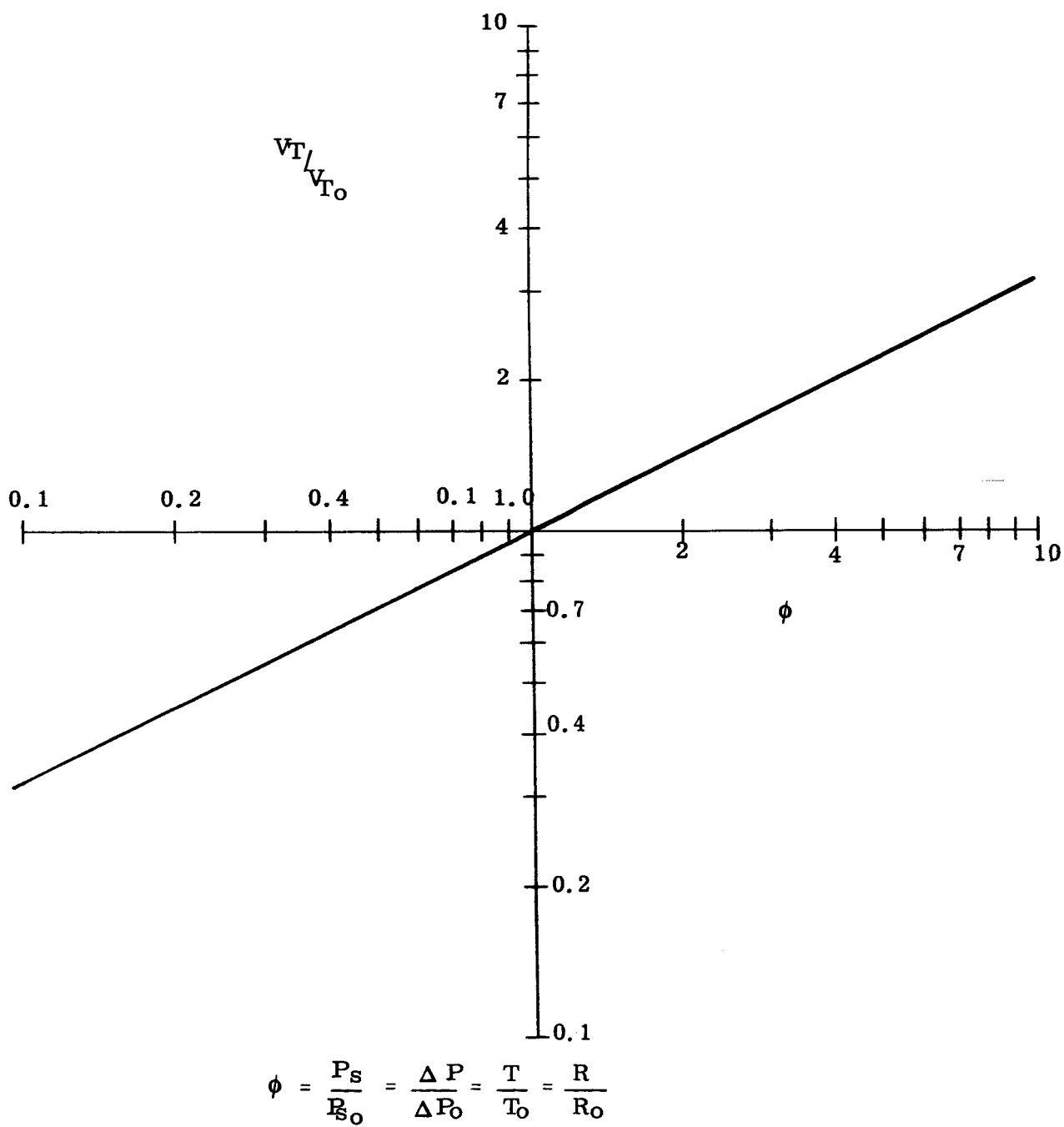
Figure 10-5. Effect of Variation of P_S, ΔP, T, R on V_T.

$$\phi = \frac{P_S}{P_{S_O}} = \frac{\Delta P}{\Delta P_O} = \frac{T}{T_O} = \frac{R}{R_O}$$

Fluid Amplifier Functions

Space Systems Categories	Sensors									Logic						Control									
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
0.0 System Applications, Functions, and Missions	X	X	X		X					X	X	X			X	X	X							X	
1.0 Boost Vehicles	X	X	X	X			X	X	X	X	X	X	X	X			X	X	X	X					X
2.0 Space Vehicles	X	X	X	X	X				X	X	X	X	X	X		X	X	X	X	X				X	X
3.0 Navigation and Control	X	X	X				X		X	X	X	X	X	X				X	X	X				X	X
4.0 Power Systems				X		X		X		X	X	X	X	X		X	X	X	X		X	X		X	X
5.0 Pay Load & Instrumentation	X	X	X			X			X	X	X	X	X	X			X	X	X	X				X	X
6.0 Structures and Other Spacecraft Subsystems						X	X			X	X	X	X	X		X		X	X	X	X		X		X
7.0 Ground Based Electronics and Optics	X	X	X			X	X			X	X				X			X	X	X	X			X	X
8.0 Ground Support and Test Equipment						X				X	X				X		X	X	X	X	X			X	X
9.0 Supporting and Advanced Technologies										X	X			X		X		X	X	X	X	X	X	X	

Consulting Areas and Personnel

1. Analog Flight Systems - M. A. Goldman
2. Flight Computers - G. T. Sendzuk
3. Flight Controls - J. S. Sicko, R. C. Wells
4. Boosters & Engines - W. R. Collier
5. Communications - C. E. Mortlock (H. A. Lavanhar)
6. Ground Support - R. Townley (J. Dysinger)
7. Timing Rate Systems - A. Donoucos
8. Engine Control - B. H. Snow (W. R. Spencer)
9. Missile Guidance - P. Boswell, J. Hannabach
10. Re-entry Systems - J. C. Carroll, L. H. Boerstler
11. Operation, Logistical and Analysis - J. C. Gelhard (S. Gaskell)
12. Spacecraft Systems - J. K. Davis
13. Space Power - D. L. Kerr
14. Propulsion Systems - G. S. Emmons
15. Space Systems Applications - J. Pinkstaff
16. Manned Space Systems - F. B. Bailey, J. Carpenter
17. Nuclear Space Systems - E. Ray (R. Cohen, J. W. Larson, W. J. Paterson)
18. Life Support Systems - G. L. Fogel
19. Bioscience & Human Factors - R. W. Lawton
20. Advanced Space Projects - P. Lathrop
21. Manufacturing Methods - B. F. Hart
22. Reliability - A. B. Carson
23. Reliability - R. H. Norris
24. General - H. Chestnut
25. Cryogenics - L. B. Nesbitt

Appendix I. Space System/Fluid Amplifier Matrix.

Appendix II

SPACE SYSTEM CATEGORIES

The space system categories used as a guide in identifying possible applications of interest to the National Aeronautics and Space Administration are shown below.

0.0 **SYSTEM APPLICATIONS, FUNCTIONS, AND MISSIONS**

    0.1 Communications

        0.1.1 Commercial

        0.1.2 Military

        0.1.3 Scientific

    0.2 Command and Control

    0.3 Instrumentation (Global Range)

    0.4 Navigational

    0.5 Geodetic

    0.6 Meteorological

    0.7 Surveillance/Reconnaissance

        0.7.1 Global

        0.7.2 Extra-terrestrial

        0.7.3 Damage Assessment

        0.7.4 Nuclear Detection

    0.8 Offense Systems

    0.9 Defense Systems

    0.10 Arms Control

    0.11 Scientific/Exploration

        0.11.1 Global

        0.11.2 Lunar

        0.11.3 Planetary

    0.12 Technological Demonstration

        0.12.1 Rendezvous

        0.12.2 Maintenance and Repair

        0.12.3 Orbit Launch

    0.13 Miscellaneous

1.0 BOOST VEHICLES

      1.0.1   Supporting Technologies and Studies

1.1 Engines

      1.1.1   Solid Fuel, Chemical

      1.1.2   Liquid Fuel, Chemical (including storable)

      1.1.3   Air-Breathing (power source chemical or nuclear)

      1.1.4   Nuclear

1.2 Structure

      1.2.1   Frames

      1.2.2   Tanks

      1.2.3   Recovery Devices (parachutes, Rogallo wing, etc.)

      1.2.4   Materials

1.3 Guidance and Control

      1.3.1   Guidance System (auto-pilot)

      1.3.2   Command Receivers

      1.3.3   Transponders

      1.3.4   Range Safety Components

1.4 Auxiliary Equipment

      1.4.1   APU's

      1.4.2   Pumps (if separate from engine)

      1.4.3   Valves, Piping, Electronic Equipment, etc.

1.5 Instrumentation and Telemetry

2.0 SPACE VEHICLES

      2.0.1   Technologies and Studies

2.1 Earth Satellites

      2.1.1   Orbit and Re-entry (manned and bio-sat)

      2.1.2   Communication Satellites

      2.1.3   Meteorological Satellites

      2.1.4   Scientific Satellites

4.0 POWER SYSTEMS

4.1 Chemical

- 4.1.1 Hot Gas Servos
- 4.1.2 Hydraulic Drives
- 4.1.3 Turbo-Machinery
- 4.1.4 Batteries
- 4.1.5 Fuel Cells
- 4.1.6 MHD

4.2 Solar

- 4.2.1 Thermoelectric
- 4.2.2 Thermionic
- 4.2.3 Voltaic

4.3 Nuclear

- 4.3.1 Thermoelectric
- 4.3.2 Thermionic
- 4.3.3 Mechanical

4.4 Power Conversion Equipment

4.5 Vehicle/Secondary Propulsion

- 4.5.1 Cold Gas Jets
- 4.5.2 Hot Gas
- 4.5.3 Solid Fuel Rockets
- 4.5.4 Electrothermal (arc-jet)
- 4.5.5 Electromagnetic (plasma)
- 4.5.6 Electrostatic (ion engine)
- 4.5.7 Materials Research

5.0 PAYLOAD AND INSTRUMENTATION

5.1 Payload (Mission Classification)

- 5.1.1 Communication
- 5.1.2 Surveillance

6.1.7   Miscellaneous Hardware - Bearings, Seals, etc.

6.2   Vehicle/Life Support Equipment

    6.2.1   Water

    6.2.2   Oxygen

    6.2.3   Food

    6.2.4 CO_2 Absorption

    6.2.5   Waste Disposal

    6.2.6   Crew Stations

    6.2.7   Seats, etc.

    6.2.8   Spacesuits

6.3   Vehicle/Safety Devices

6.4   Vehicle/Recovery Equipment (includes parachutes, Rogallo wing, etc.)

7.0   GROUND BASED ELECTRONICS AND OPTICS

    7.0.1   Supporting Technologies and Studies

7.1   Guidance Systems (both ground and space borne)

    7.1.1   Radio

    7.1.2   Inertial

    7.1.3   Combination

7.2   Fire Control

    7.2.1   Computers

    7.2.2   Monitors and Displays

7.3   Ground Tracking and Command Systems (both ground and space borne)

    7.3.1   Tracking

        7.3.1.1   Radar

        7.3.1.2   Infra-red

        7.3.1.3   Optical

        7.3.1.4   Orbit Determination

    7.3.2   Command

    7.3.3   Safety Monitors

    7.3.4   Re-entry Guidance (energy management)

    7.3.5   Computation

Appendix III

SCHEMATIC SYMBOLS FOR FLUID TRANSISTORS AND CIRCUITRY

III.1 INTRODUCTION

This section describes the system of symbols used in this report. The material is taken from a paper presented at the Fluid Amplifier Symposium, of the Harry Diamond Laboratories, October 1962, by Dr. J. N. Shinn and Mr. W. A. Boothe. These symbols were used to give a consistent, simple means of representing the circuits discussed in the report. This system is not accepted as a standard of the technology. No such standard exists.

III.2 FUNDAMENTAL DELINEATIONS

Fluid amplifiers can be categorized in many ways. However, several basic questions about a fluid amplifier element come to mind immediately. Is it digital or analog in nature? Is it a beam-deflector type element or a vortex type element? Is it active or passive? These questions can be answered quite simply in schematic form. The flow path of the power jet of an analog valve is denoted with a dashed line, whereas a digital element is represented with solid lines throughout. Figure III-1 shows this usage applied to simple beam deflector amplifiers. The use of the enclosing circle around the element is optional. In simpler schematics it is not used, while in more complicated ones it makes the element stand out from the connecting lines. The input and output lines of the elements appear in the schematic at the same points where they normally would on the actual element, as pointed out in Figure III-1. Figure III-2 shows the symbols used for vortex amplifiers which may also be digital or analog in form.

As shown in Figure III-3, the designation as to whether or not a valve is active or passive is done by means of a solid circle at the base of the power nozzle line to indicate that this line is connected to the circuit supply pressure. If more than one pressure supply level is used in a circuit, a letter or number code can be used to differentiate between them.

III.3 SCHEMATICS FOR ANALOG DEVICES

The basic form of analog valve symbols are given in Figures III-1b and III-2b, where the main distinguishing feature is the dashed line to represent the flow path of the power jet. The possible variations of these basic representations are so numerous that they can not be covered completely in this writeup. However, one shorthand representation believed worth mentioning is that of the operational amplifier. Figure III-4a shows an arbitrary example of a schematic for a high-gain, four-stage, operational amplifier. The outputs in this example will be a function of the difference between input A and input B, the function depending on the feedback impedances Z_1 and Z_2 which provide in this instance negative and positive feedback, respectively. Figure III-4b shows the shorthand symbol for the same circuit. In this symbol the asterisk is used to indicate the sense or polarity. For example, in Figure III-4b, this notation indicates an increase in input A which results in an increase in output C to correspond with the circuit in Figure III-4a. If an odd number of stages were used, the asterisk would, of course, appear behind D. This convention permits the schematic to have close correspondence with the physical circuit layout.

III.4 SCHEMATICS FOR DIGITAL DEVICES

The schematic for a basic Flip-Flop (Figure III-5) is quite similar to the physical layout of the device. An input of A will cause an output at D and an input at B will switch the flow to C. The symbol for a fluid source indicates that the Flip-Flop in the example is an active device. The schematic for the binary Flip-Flop, such as the counter stage developed by R. W. Warren at the Diamond Ordnance Fuze Laboratory, is shown in Figure III-6. Input pulses at A switch the flow alternately to outputs C and D. A reset signal pulse applied at the RS input will switch the second stage jet to output D. The schematic indicates the second stage of the binary Flip-Flop to be an active device.

The schematic for an active OR-NOR element is shown in Figure III-7a. Inputs at C, D, or E will cause an output at B, thus performing the OR function. With no input signal the output is at A, performing the NOR function.

Using conventional logic notation, the element is identified as an OR-NOR by including the + sign. The choice of three inputs for the example in Figure III-7a was arbitrary; an "N" input element would be shown schematically with "N" input lines. Figure III-7b shows a passive OR element.

Figure III-8 shows the schematic for the active and passive AND elements. Using standard logic notation for an AND, the function of the element is identified by a dot. An output at B will occur only when inputs C, D and E are all present.

The Half-Adder, or Exclusive-OR, schematic is shown in Figure III-9. An input either at C or at D, but not both simultaneously, will provide an output at B while simultaneous inputs at C and D provide an output at A. The Half-Adder can also be used as a two-input AND element. This schematic follows closely the general physical layout of one form of a Half-Adder now in use. Although Half-Adders quite different from that shown in the schematic have been devised, this schematic was chosen because it is believed to represent simply and clearly the functioning of the Half-Adder element.

III. 5 MEMORY AND BIASING

Some devices have memory and thus can operate with input signals in pulse form, while others require a continuous input signal for operation. This difference in operating characteristics is delineated on the schematics as illustrated in Figure III-10. The arrowheads on the input lines indicate that a continual flow is required to maintain the state of the element. Note that in Figures III-7, III-8, and III-9, this notation was used to indicate that steady-state inputs are required to provide the desired performance.

Bias signals are often used to provide desired characteristics. Figure III-11 illustrates how a bias signal would be represented schematically on a Flip-Flop and an OR element. If an AND or OR element is shown without the biasing input line then it is implied to be geometrically biased.

III. 6 OTHER CIRCUIT ELEMENTS

A fluid circuit would not be complete without the many passive impedance

elements, such as orifices or restrictions and without showing connections, such as vents or drains. To do this, extensive use has been made of the Joint Industry Conference (JIC) practice where practical.

Figure III-12a shows the general symbol for impedance. Figure III-12b shows the representation for an orifice which would obey a square-law relationship if an incompressible fluid is used. (No attempt is made here to differentiate between a choked and unchoked flow if the fluid is compressible.) Figure III-12c represents a laminar restriction where pressure drop varies linearly with flow and where friction effects predominate over inertial effects. Figure III-12d in turn shows fluid inductance where inertial effects predominate over friction. A relatively pure fluid inductance is found primarily in liquid circuits.

Figure III-12e shows the symbol for a fluid capacitor which, in some instances, is analogous to an electrical capacitor. A fluid capacitor consists of a fixed volume if the fluid is compressible, or a hydraulic accumulator or equivalent for an incompressible fluid. In drawing an electrical analogy, where voltage and current are analogous to pressure and flow, respectively, a fluid capacitor such as the volume or accumulator can only be the equivalent to shunt capacitance from the point in question to ground. It is never the equivalent of a blocking capacitor. The equivalent of blocking capacitors must be obtained by using other devices.

Figure III-12f shows the symbol for a fluid delay line which has the characteristic of providing a pure time delay in the signal transmitted with a minimum of attenuation.

Figures III-13a and III-13b show that crossing and connecting lines follow a practice identical to JIC hydraulic practice as well as some electrical standards.

Vent connections are shown in Figure III-13c and should be used in any open-cycle circuit where the excess fluid is merely vented to atmosphere or drained off.

If a closed-cycle circuit is used, the excess and exhaust fluid must be returned to the reservoir. To decrease the number of lines in the schematic, it is recommended that the JIC symbol of Figure III-13e be adopted.
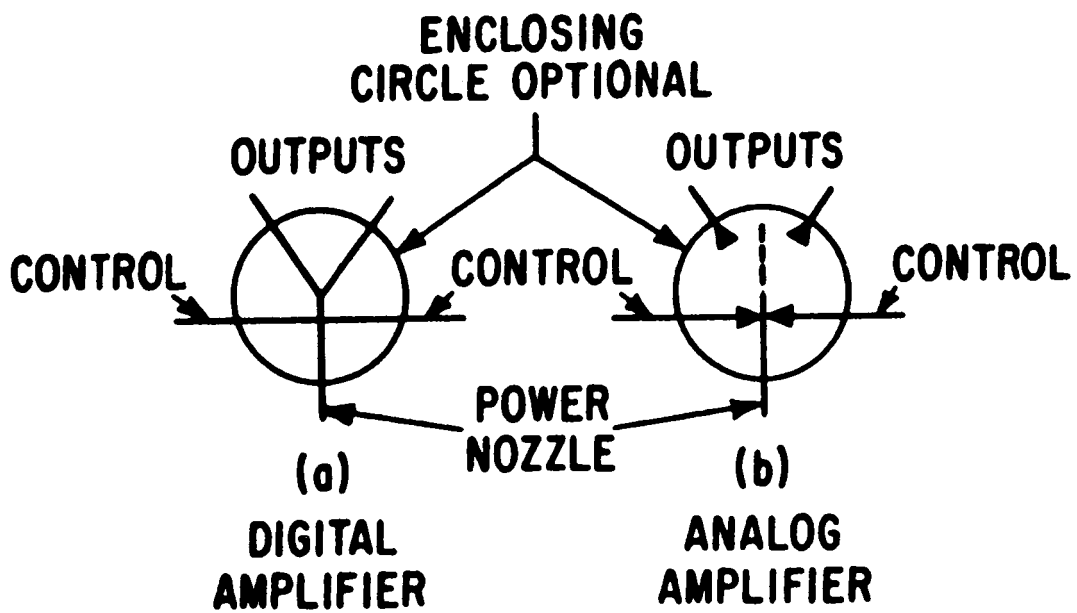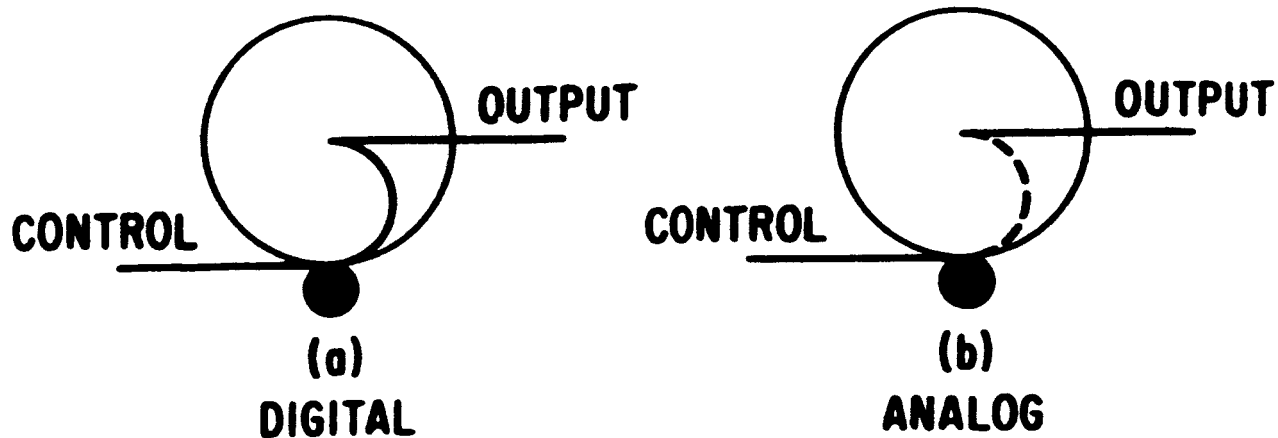
Figure III-1. Beam Deflector Amplifiers.
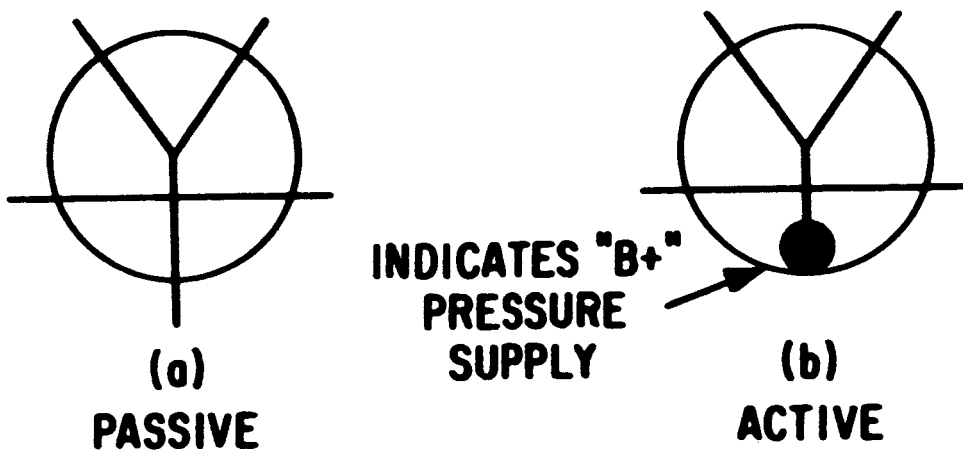
Figure III-2. Vortex Amplifiers.

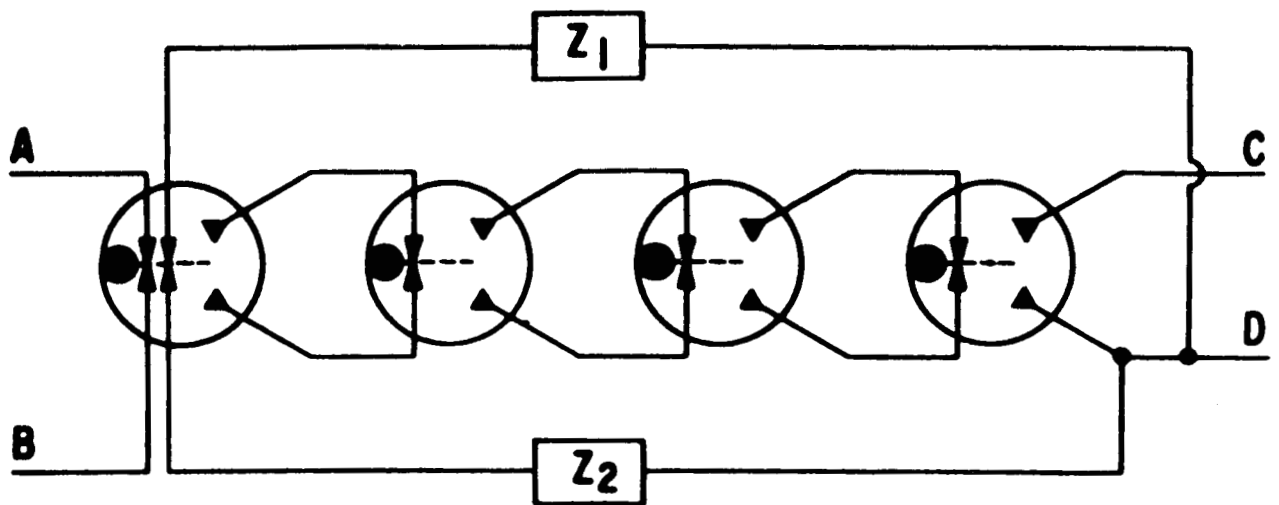Figure III-3. Designation of Active Versus Passive Elements.
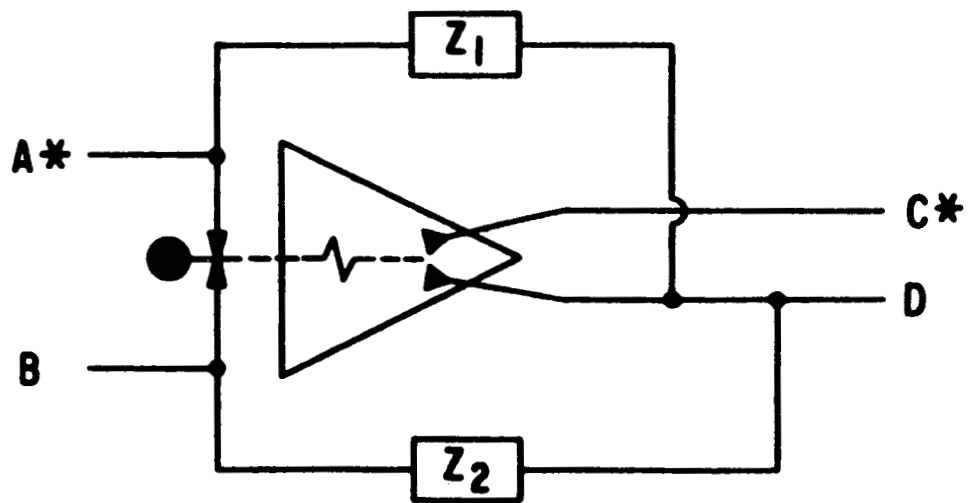
Figure-III-4a. Four-Stage Operational Amplifier.
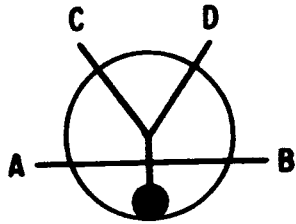

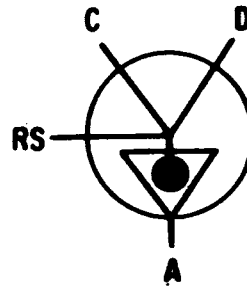Figure III-4b. Operational Amplifier.

Figure III-5. Basic Flip-Flop.

Figure III-6. Binary Flip-Flop

(a)
ACTIVE
OR-NOR

(b)
PASSIVE
"OR"
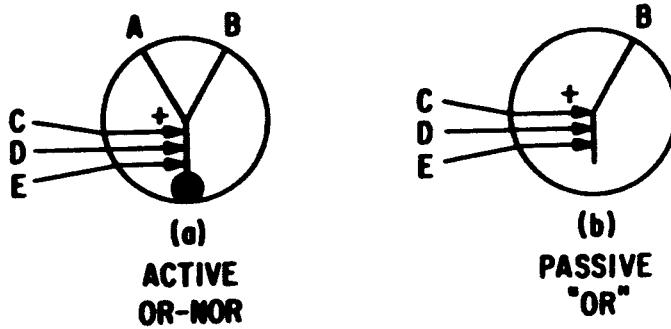
Figure III-7. OR Logic Elements.

(a)
ACTIVE

(b)
PASSIVE
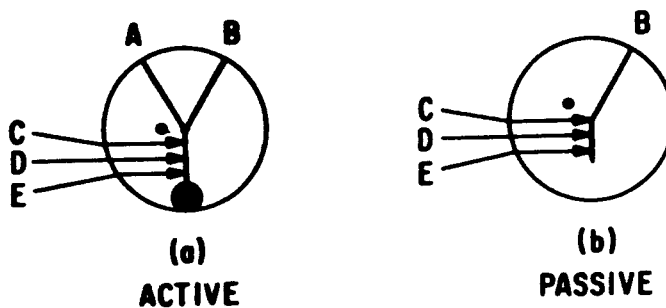
Figure III-8. AND Logic Elements.
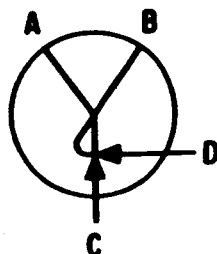
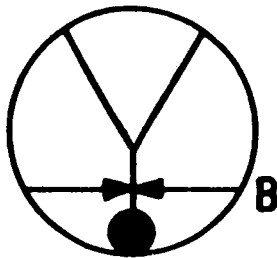Figure III-9. Half-Adder, Exclusive OR.
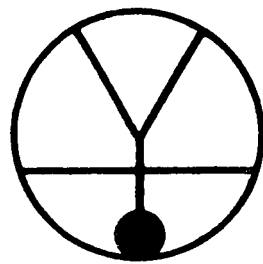
(a)
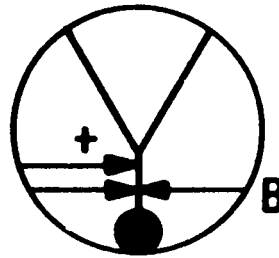**MEMORY**
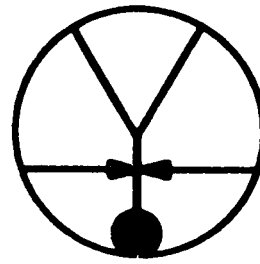
(b)
NO MEMORY

Figure III-10.   Flip-Flops with and without Memory.

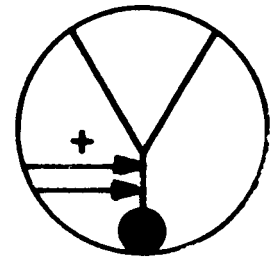**(a)**
BIASED FLIP-FLOP

(b)
"OR"-SIGNAL BIASED

(c)
**"OR"-
GEOMETRICALLY
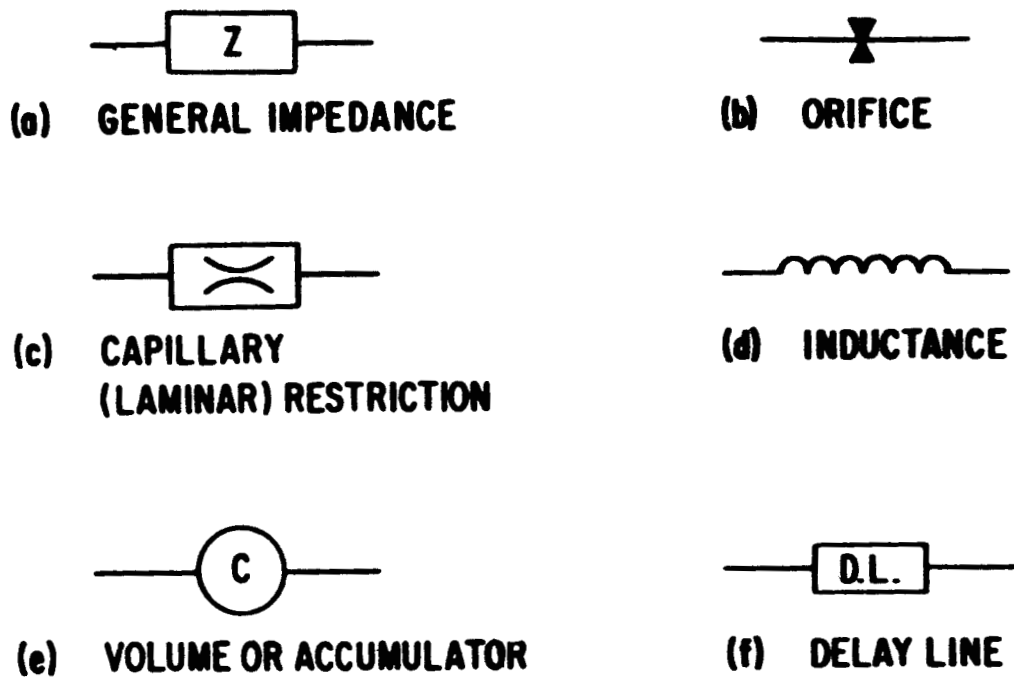BIASED**

Figure III-11.   Representation of Biasing Signals.

(a) GENERAL IMPEDANCE

(b) ORIFICE

(c) CAPILLARY (LAMINAR) RESTRICTION

(d) INDUCTANCE

(e) VOLUME OR ACCUMULATOR

(f) DELAY LINE

Figure III-12. Symbols for Line Impedances.

(a) CROSSING LINES

(b) CONNECTING LINES

(c) VENT CONNECTION

(d) EXAMPLE OF VENT
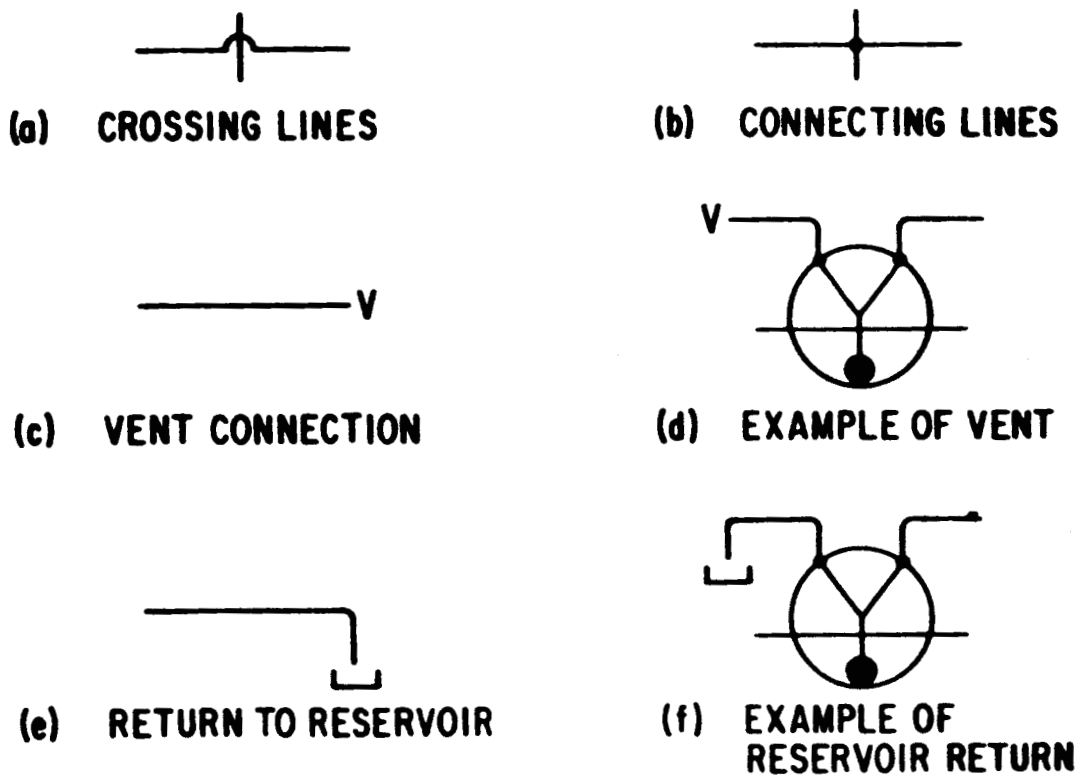
(e) RETURN TO RESERVOIR

(f) EXAMPLE OF RESERVOIR RETURN

Figure III-13. Symbols for Connections.